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A NEW CHRONOSCOPE AND FALL APPARATUS

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Certain well-defined principles in physics which are, perhaps, not very familiar to the worker whose interest lies in other fields of science, lend themselves admirably to the measurement of time intervals of the order of magnitude in which the psychologist is especially interested. In this paper these principles are to be set forth as non-technically as possible; and a method for applying them to the purpose mentioned, requiring no intimate knowledge of the principles, will be described. The outcome of such application is a new chronoscope which, considering its simplicity, yields measurements of remarkable accuracy.

In considering the principles, an analogy from hydraulics is of service, namely the flow of water in a pipe. The strength of a current of water (gallons-per-second) multiplied by the time (seconds) during which the current flows gives the total quantity (gallons) which has passed through the pipe during the interval in question. Exactly the same relations hold in the case of electricity flowing in a circuit. The product of current strength (amperes) and time (seconds) gives the total quantity of electricity (coulombs) which has passed through the circuit during the time interval. This suggests the following possibility: let a current of known strength be sent, during a time interval to be determined, through a circuit in which there is a device for measuring the quantity of electricity—a device analogous to a water meter, to continue the comparison. The value of the time interval is obtainable from

[1] Physical Laboratory.

the relation above mentioned; expressed algebraically, $t = Q/I$, where t is the time interval, Q the quantity, and I the current.[1] The current might, of course, be measured by one of several methods; and the moving coil galvanometer, of the type possessed by most psychological laboratories, is an instrument which is applicable to the measurement of electrical quantity.

Any quantity of electricity of sufficient magnitude, when discharged through a galvanometer, produces a 'throw' or swing of the coil through a certain angle, whence the coil immediately begins its return towards its position of rest. The angle is a function of the total quantity which has passed. When the rate at which the quantity passes is constant, in other words, when the current is unchanging in strength during the interval in which it flows, the quantity of electricity is calculable from the observed angle of throw. This fact has been made the basis for the measurement of time intervals as long as five seconds and more with an accuracy of a few thousandths of a second.[2] When the time interval to be measured is short, say of the order of 1/30 of the time required by the coil to execute one complete vibration, the throw is, for practical purposes, directly proportional to the quantity, and therefore, with a given current strength, to the time interval. It thus becomes possible to construct a galvanometer scale to indicate time intervals directly, with any desired range up to half the time occupied by one complete vibration of the coil. For very short intervals, corresponding to those, for example, of reaction time, the scale will be one of nearly equal divisions.

The innovation, however, of constructing a direct-reading time scale for a galvanometer, is of small value *per se*. In addition, some method should be devised which will produce exact correspondence between the scale readings and the time

[1] We observe that the same relation holds for the current of water. If, for instance, we know that a current of I gallons-per-second is flowing in a pipe, during an unknown interval of t seconds, then a reading of the water meter, giving the number of gallons, Q, which passed during the interval, enables us to calculate the value of t by the formula above given. Thus, with a fixed strength of current, the reading of the water meter is proportional to the time interval during which the water was flowing.

[2] Klopsteg, *Physical Review*, 8, 195, 1916.

intervals represented by them. One method, as has already been intimated, would be to make such control depend upon measurements of electrical current and quantity. If there were no other way, however, the method would be inapplicable except in the hands of an experimenter trained in making such determinations. The simplification which renders the use of the galvanometer as a chronoscope practicable, even on the part of an experimenter unfamiliar with the principles, is a new fall apparatus which, with the aid of a simple switchboard for the electrical adjustment, enables one easily and accurately to control the galvanometer readings.

Description of Electrical Connections.—For the purpose of sending a constant current through the galvanometer during any short time interval, an arrangement, the most important features of which are shown in Fig. 1, is used. A lead storage

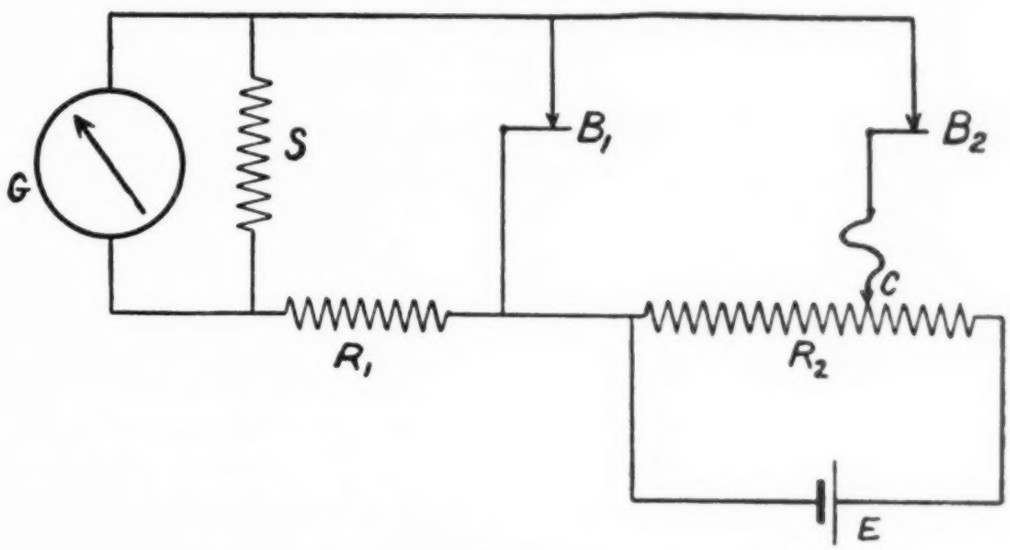

FIG. 1

cell is connected, as shown, to the terminals of a wire resistance R_2. By connecting one side of the galvanometer circuit to one of these terminals, and the other to a sliding contact C, which bears on the wire of R_2, we are enabled to impress any desired potential difference smaller than that of the cell upon the galvanometer, and thus cause a current of desired strength to pass through the instrument. In series with the galvanometer G is connected a high resistance R_1. To diminish the

likelihood of error in the measurement of an interval because of the fact that the current may not start exactly at the initial instant, nor be cut off exactly at the final instant of the interval, these instants are marked, preferably, by two breaks in the electrical connections, rather than by a make and a break. That is to say, the current should begin to flow through the galvanometer at the instant of breaking one connection, and cease at the instant of breaking a second connection. These are shown at B_1 and B_2 in the figure. The purpose of the high resistance R_1 is now evident: it renders the resistance of B_1 negligible in comparison with R_1 and the combination of G and S. This arrangement permits of no leak through the galvanometer before B_1 is opened. S is a shunt which produces critical damping of the galvanometer coil. In this condition the coil is, in the language of the engineer, 'dead beat,' and cannot pass the position of rest, or zero position, when returning from a throw.

Description of Complete Apparatus.—The complete chronoscope, arranged for the measurement of unknown intervals and for immediate determination of the accuracy of its indications, consists of the following three parts: galvanometer, fall apparatus and switchboard for electrical control, together with the necessary batteries. The component parts will be considered in detail.

Galvanometer.—In the writer's experimental setup, the galvanometer was one of the Leeds and Northrup type P instruments. Its time of throw, *i. e.*, the time required by the coil to make its excursion from the position of rest to its extreme displacement—which time is the same for all angles of throw—was adjusted to be about 2.5 seconds. With this time it is an easy matter to obtain the reading indicated at the extremity or turning point of the displacement. The coil was provided with a 'damping rectangle'[1] to assist in making the motion dead beat. The particular advantage of this degree of damping, in connection with the use of the galvanometer as a chronoscope, is the fact that the instrument

[1] Klopsteg, *Physical Review*, 3, 121, 1914; *Zeitschrift für Instrumentenkunde*, 34, 338, 1914.

is self setting to zero. A reading of the instrument is taken, let us say; by the time the observer has prepared for the following observation, the coil has returned to the zero position without oscillation, and is ready for the next reading. It is thus possible to obtain four or five observations a minute.

Two types of scale may be used. One which was found to be particularly convenient was translucent. Upon it the galvanometer throws were indicated by means of a vertical dark line extending through a spot of light. The spot, which was reflected from the mirror attached to the coil, was produced by an incandescent lamp attached to the scale, both scale and lamp having been affixed to the galvanometer. The other scale is the usual type, ruled on a white surface, and read by means of a telescope, the eyepiece of which is provided with a fine vertical crosshair. The advantage of the first type of scale is that of ease in reading, although the mean variation in a given number of measurements of the same interval may be somewhat greater than that resulting when the other type of scale is used. However, with this latter type, if the telescope is properly adjusted, a great number of readings can be taken without undue eye strain. Both scales were ruled for a range of 500 σ; on the translucent scale, each division represents 2 σ, while the other has one division per σ.

Fall Apparatus.—Bearing in mind that the initial and terminal instants of the interval to be measured are, at least in the control apparatus, to be marked by two breaks of electrical circuits, we observe this to be the problem in the design of the apparatus: to obtain exact coincidence between each of these two instants, respectively, and the corresponding break of a circuit. A fall apparatus, with a one-inch smooth iron or steel ball as the falling body, was chosen, for the reason that the distances of fall corresponding to certain time intervals can be accurately calculated, and that for the short intervals involved in these measurements, the air resistance to such a ball introduces no appreciable error. These circumstances—provided the coincidences above mentioned can be realized—render the fall apparatus independent of any other control, such as a tuning fork, for example. In Fig. 2 is shown the

apparatus which fulfilled the requirements with complete success. *E* is an electromagnet which, at the desired instant, upon the breaking of its energizing circuit, releases the iron ball. The latter, in falling, strikes the lever *A* which norm-

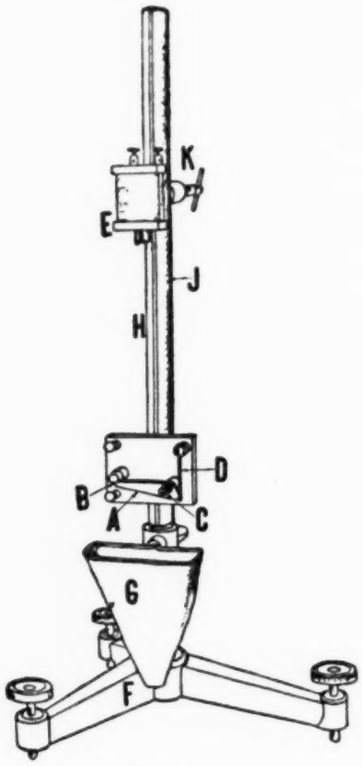

FIG. 2

ally makes contact at the point *B*; finally the ball is caught in the bag *G*. The release magnet, break switch and bag are all mounted on the rod *H* which, in turn, is supported by the tripod base *F*. The base is provided with levelling screws by means of which the axis of the magnet and middle point of the break lever can be brought into the same vertical line. The rod *H* carries the time scale *J* which indicates directly the time occupied in the descent of the ball from the magnet to the break lever. By means of the indicator *K* the position of the magnet is read on the scale *J*. The contact lever of the break switch pivots on the screw *C*. Electrical contact is assured by the fact that the leaf spring *D* bears upon the heel of the contact lever; on the other hand, after the falling ball has struck the lever, the latter is pushed out of the way and

held there by D, thus keeping the circuit open until the switch is intentionally closed. The range of the fall apparatus depends upon the length of the rod, but anything greater than $500\,\sigma$ seems unnecessary, as will appear later; in fact $400\,\sigma$ has been found sufficient for every purpose.

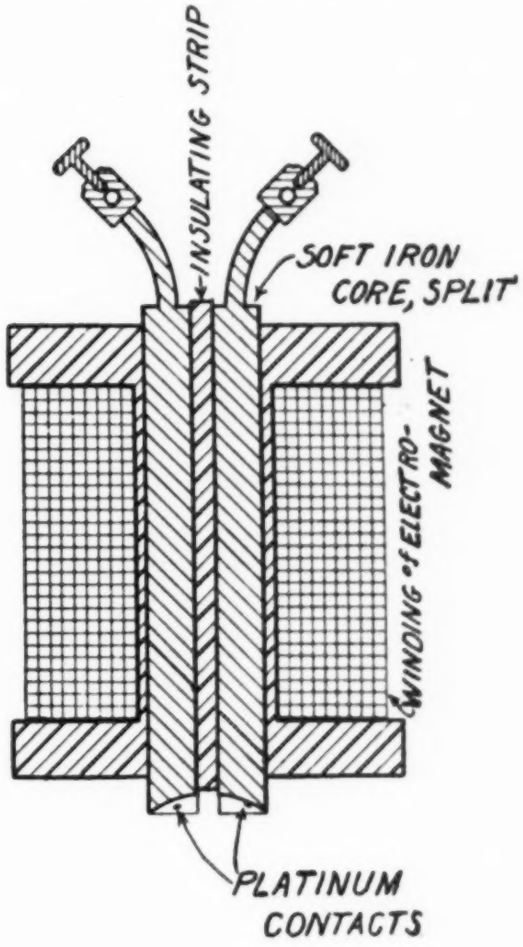

FIG. 3

In Fig. 3 is shown a cross-sectional diagram of the release magnet, which indicates how error in the time interval 'measured out' by the apparatus is obviated. As shown, the core of the magnet is split, with an insulating strip between the halves. Each of the halves is provided with a binding post. The winding is carefully insulated from the core. The latter is cupped at its lower end, so that it may hold the ball firmly. Three or four equally spaced platinum contacts are soldered into the cup, for good connection. It will be noticed

that when the ball is in place, and the halves of the core are connected in shunt with the galvanometer, the ball itself plays the rôle of B_1 in Fig. 1. All the current flows through the ball, not any through the galvanometer. Coincident with

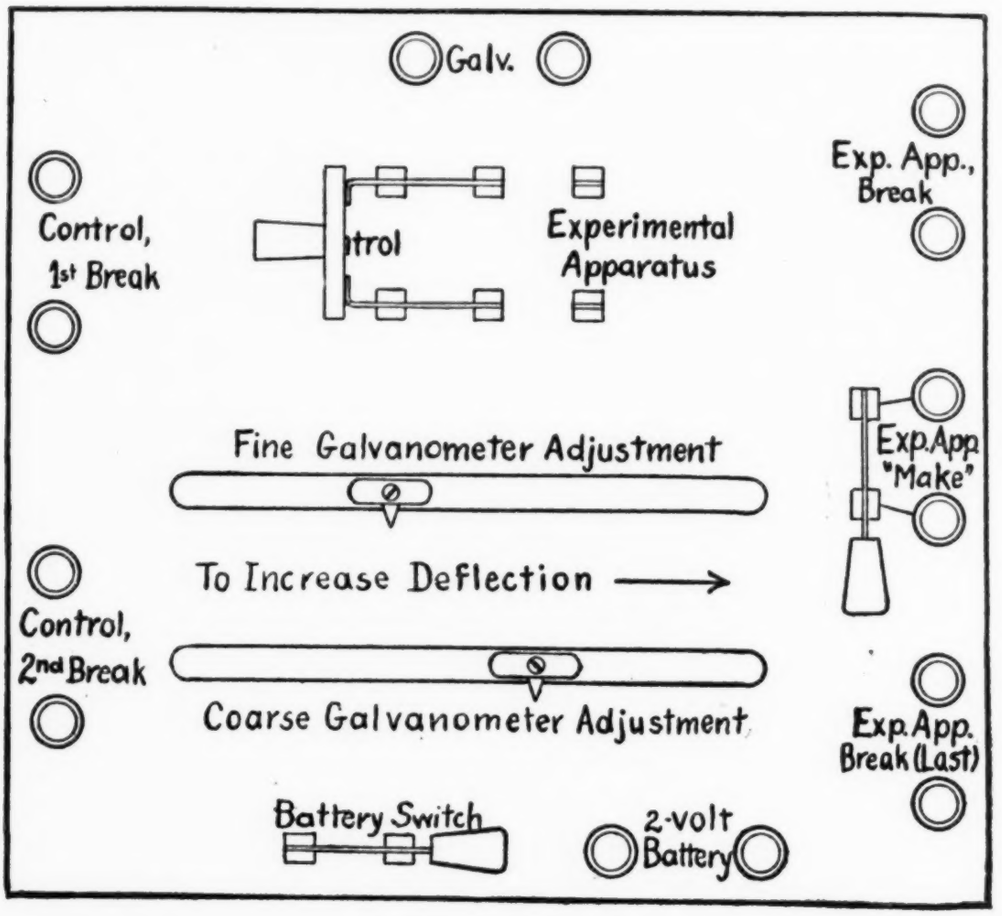

FIG. 4

the instant of release of the ball—and it should be emphasized that there is no other possibility besides coincidence—the current starts through the galvanometer, and continues until the instant at which the lever A is struck by the ball. The lever is represented by B_2 in Fig. 1. We are now able, by clamping the magnet at any desired position, as indicated on the scale J, to send a current through the galvanometer during the exact interval indicated.

Switchboard.—To make the manipulation of the chronoscope as simple as possible, the switchboard shown in Fig. 4

was designed.[1] All resistances indicated in Fig. 1 are mounted beneath the board. The entire board is so labeled that proper connections are easily made without possibility of error. With the double throw switch in the position shown, the control apparatus is connected to the chronoscope. Throwing this switch to the right connects the galvanometer and its necessary electrical attachments with, say, the reaction time apparatus, consisting presumably of a circuit for the stimulating mechanism, and of a reaction key circuit. It is best, in this apparatus, as in the control apparatus, to use two breaks. When this is not possible, a make may be used to effect the stimulation, followed by a break, made by the reaction movement.

Accuracy.—Although different galvanometers of the same type manifest individual differences, due principally to irregularities in their magnetic fields, still the performance of the instrument used by the author is quite typical of this particular kind. The galvanometer used in these measurements was not specially selected, but was taken because it was one of seventeen instruments not in use in the undergraduate laboratory. In taking the readings of the accompanying table, the fall apparatus was set for 300 σ, and the adjustment of the chronoscope made for zero constant error at this point. Having made this adjustment, the release magnet was set successively at 400, 350, 300, 200 and 100 σ, without further electrical adjustment, and ten readings were taken with the telescope and scale for each setting of the magnet. In the table the whole series of observations is given.

Particular attention should be called to the fact that for 100 σ, the distance the ball falls is but 4.903 cm. The observed values, considering that adjustment was made for zero constant error at 300 σ, are remarkably accurate, indicating that practically no error is introduced at the instants of starting and stopping the current by means of the apparatus. The results indicate that one is quite justified in assuming carefully made

[1] Improved designs of both release magnet and switchboard, involving the same principles as above described, have recently been worked out. The manufacture of the entire apparatus has been undertaken by the Leeds and Northrup Company of Philadelphia.

observations upon reaction times to give results which are safely within one σ of the true intervals. This will be especially true if the adjustment for zero constant error is made for an interval having somewhere near the mean value of the reaction intervals.

Fall Apparatus Set at—				
400	350	300	200	100
401.5	350.3	300	199.6	100.4
401.5	350	300	200	100
400.5	350	300.4	199.5	100
401.5	350	300	199.6	100
401	350	300	199.5	99.8
400	350.5	299.5	199.5	99.6
401.5	350	300	200	100
401	350	300	199.5	100.2
401	350	300	199.5	100
400.5	350	300	200	100
Av.....401	350.1	300	199.7	100
MV, σ..... .42	.13	.10	.20	.12

Summary

The present paper describes a simple form of chronoscope, especially suited to the measurement of intervals up to 500 σ, though adaptable to greater or smaller ranges. It consists of a galvanometer with a direct reading time scale, the indications of the scale corresponding to the intervals during which a steady current is permitted to flow through the instrument. The calibration of the scale depends upon the known relation between the total quantity of electricity which has passed through the galvanometer during a given time interval, and the length of this interval. As a means of adjustment and control of the scale readings, a new fall apparatus is described which accurately 'measures out' to the chronoscope any time interval within the range of the latter.

The advantages to be pointed out for this chronoscope with its fall apparatus are:

1. Great simplicity, combined with accuracy and ease of manipulation. Every part of the scale of the chronoscope is subject to immediate standardization, merely by throwing over a switch, and dropping a ball from a certain point, corre-

sponding to the point on the scale which is under test. The fall apparatus is constructed in such a way that no observable error can enter into the time interval which it determines. The probable accuracy of a single reading is easily within one σ of the true interval, and the mean variation in ten readings for the same interval is, for the most part, less than one half σ.

2. Absolute silence during operation. The only moving part is the galvanometer coil, suspended by means of an elastic metallic fiber.

3. Automatic return of the indicator to the zero reading, and rapidity of operation, making possible about four observations per minute.

4. Possibility of demonstrating measurement of short intervals to an audience. This merely requires a different arrangement of lamp and scale from that described in this paper—an arrangement such that the audience can easily follow the motion of the indicator, permitting each person to make his own observation.

5. The fall apparatus can be used apart from this chronoscope for obtaining an accurate check upon other devices.

Note added July, 1917.—Since the above paper was first prepared Dr. Herbert Woodrow and assistants have used the writer's apparatus for a series of about 6,000 observations upon sound reaction. The apparatus functioned perfectly throughout this work, during the course of which it was transported and set up in another laboratory. To Dr. Woodrow the writer wishes to acknowledge his gratitude for the time spent in giving him the psychologist's point of view in the design of the apparatus.

THE ESTIMATION OF DISTANCES BY SIGHT AND PASSIVE TOUCH: SOME INVESTIGATIONS INTO THE EVOLUTION OF THE SENSE OF TOUCH

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I. (*a*) INTRODUCTION

This investigation is a direct continuation of the author's article 'Grössenauffassung durch das Auge und den ruhenden Tastsinn,' published in *Archiv für die gesamte Psychologie*, Vol. XXXII., p. 420 ff.

The first part of this article will be devoted to an attempt at a biological explanation of the general law from the point of view of adaptation. The second part will present the results of fresh experiments conducted with children of various ages, further verifying the general law and its biological significance.

So as to establish continuity between the earlier investigation and this, a brief résumé of the main points will be given.

(*b*) METHODS OF EXPERIMENT, APPARATUS, FORMULÆ, ETC.

The general problem is: How accurately do we estimate distances (above the space-threshold) presented to passive touch by means of two, simultaneously given, unmoved points?

The tactile distance was compared with the visual in each case, the presentation of the two impressions being successive. The method used was the Constant-method, with full rows of the variable stimulus, the distances following each other not consecutively, but as drawn by chance. As a rule 5 rows of the variable stimulus formed the basis of each calculation for the equivalent-value.

To calculate this equivalent-value the following Spearman[1]-Wirth[2] formulæ were used:

$$\text{Upper Threshold, } r_0 = E_0 - i\Sigma g + \frac{i}{2},$$

$$\text{Lower Threshold, } r_u = E_u + i\Sigma k - \frac{i}{2},$$

wherein Σg is the sum of all the 'greater' and Σk of all 'smaller'-judgments, in their relative frequency, E_0 and E_u are the first extremes beyond which no more 'greater' or 'smaller'-judgments are given, and i is the interval between consecutive distances in the variable stimulus.

$$\text{The equivalent-value } A = \frac{r_0 + r_u}{2}.$$

For calculation of the spread or distribution of the decisions ('Streuungsmasse'), Wirth's formulæ[3] were used. M_0 is the value of the spread or 'Streuung' with reference to the upper threshold, M_u with reference to the lower threshold, and M is the value of the total 'Streuung.'

$$\frac{\mathbf{I}}{i^2}(M_0)^2 = 2[(p-1)g_1 + (p-2)g_2 \cdots + 1 \cdot g_{p-1} + \tfrac{1}{8}] - (\Sigma g - \tfrac{1}{2})^2,$$

[1] *Brit. Jour. of Psy.*, Vol. II., 3, 1908, p. 227 ff.
[2] *Psychophysik*, 1912, pp. 188 and 189.
[3] Wirth, *Psychophysik*, 1912, p. 192.

$$\frac{1}{i^2}(M_u)^2 = 2[(q-1)k_1 + (q-2)k_2 \cdots + 1 \cdot k_{q-1} + \tfrac{1}{8}] - (\Sigma k - \tfrac{1}{2})^2,$$

$$M = \sqrt{\tfrac{1}{2}(M_0^2 + M_u^2 + 2S^2)},$$

in which $2S = r_0 - r_u$.

The visual distance was presented by means of two black dots on a white card which stood perpendicularly at normal seeing-distance from the observer. In the first investigation and in the experiments with the German boys the tactile stimulus was given by means of an Ebbinghaus æsthesiometer (applied electrically), but by means of a Spearman æsthesiometer (applied by hand)[1] in the experiments with the Grahamstown boys embodied in this investigation. Whilst the tactile stimulus was being given, the card with the dots was covered. Throughout each series of experiments the æsthesiometer and the stimulated portion of the skin were hidden from view by a screen. The time-order, which was regulated in both investigations by a metronome, was as follows:

Interval between signal ('Bitte,' 'ready,' etc.) and the first stimulus, and between the first and second stimulus: each one second. Duration of each stimulus: as a rule 2 seconds.

The details of the stimulation were unknown, except that the observer knew which part of the skin was to be stimulated and in which direction (across or along).

The order of succession of the two stimuli which was found most successful with the adults, viz., visual stimulus as normal stimulus followed by tactile stimulus as variable, was adopted throughout with the boys.

The total length of the sittings varied from about 5 minutes with the 6-year-olds to about 20 minutes with the 14-year-olds. Even these were broken up into smaller periods, as a rule two or more boys relieving one another in turn.

[1] Careful manual stimulation is quite adequate for ordinary purposes, a view recently supported by Carnes & Shearer, in *Amer. Jour. of Psy.*, Vol. XXVII., 3, July, 1916, p. 417 ff.

II. (*a*) The General Law of the Relation between the Space-threshold and the Estimation of Two-point Distances

Those parts of the skin which have very small space-thresholds overestimate two-point distances, the overestimation gradually decreasing with increase of the threshold until the indifference-point is reached where the estimation is correct. Increase of the threshold beyond this point brings underestimation, and the greater the increase the greater the underestimation.

In order to represent some of the original details, the average results for the adults and those for one of the individuals *M* will be reproduced here.

The results given are for the following parts of the skin:

1. Volar side of the first phalange of the forefinger-middle-lengthwise-right hand (short 'Forefinger').

2. Volar side of the second phalange of the second finger-middle-lengthwise-right hand (short 'Second finger').

3. Mounds or cushions of the hand-across-right hand (short 'Cushions of hand').

4. Back of hand-across-about 35 mm. from the knuckles-right (short 'Back of hand').

5. Volar side of the forearm—between middle and wrist—lengthwise towards thumb-side—right (short 'Forearm').

6. Back of neck—little to right of center—lengthwise (short 'Back of neck').

In the experiments with the boys, the parts of the skin were 1, 3, 4 and 5 of the above, making allowance in 4 for the difference in the size of the hand.

The symbols M_0, M_u, M, E_0, E_u, r_0 and r_u in the tables are as explained in the formulæ above. N is the length of the visual distance which was given first as constant stimulus and A the calculated value of the tactile distance which was judged equal to it. The amount of error involved in the tactile estimation, calculated to a percentage, is indicated briefly as 'error.' An overestimation is indicated by + and an underestimation by −. All measurements are given in millimeters.

TABLE I

OBSERVER *M*

Skin-locality	Space-thresh-old	*N*	*A*	Error Per Cent.	M_o	M_u	*M*	E_o	r_o	E_u	r_u
1. Forefinger	2.65	18	16.8	+ 6.7	4.08	3.74	4.12	20	18.1	14	15.5
2. Second finger	7.5	9	8.8	+ 2.2	2.29	3.93	3.42	11	10	6	7.6
3. Cushions of hand	11.4	32	32.3	− 1	2.93	6.77	5.40	35	33.7	28	30.9
4. Back of hand	18.2	35	37.9	− 8.3	4.66	6.62	5.81	41	38.9	34	36.9
5. Forearm	34.6	58	71.4	−23.1	7.63	5.74	7.31	80	74.2	64	68.6
6. Back of neck	48.25	38	60.1	−58.2	10.39	7	9.18	67	62.5	55	57.7

TABLE II

AVERAGES FOR ADULTS

Skin-locality	Space-threshold	Error Per Cent.	M_o	M_u	*M*
1. Forefinger	2.23	+25.2	4.11	3.70	4.24
2. Cushions of hand	6.83	+ 1.8	4.62	4.87	5.02
3. Back of hand	16.83	−10.3	8.73	8.40	8.82
4. Forearm	28.6	−58.8	15.40	21.75	19.30

(*b*) THE RELATION BETWEEN THE ACCURACY OF THE ESTIMATION AND THE ABILITY TO VISUALIZE THE PRESSURE-POINTS

The main factor in the explanation of the general law was the ability for 'passive visualization' of the points of the skin stimulated.[1] This varies inversely to the size of the threshold. As an immediate experience it appears in the different degrees of 'liveliness' of the tactual impression. Thus the variable law of estimation is really a statement of the different degrees of coördination between sight and pressure corresponding to the different parts of the skin-surface. The parts with the closest coördination exaggerate the two-point distance and those with the least coördination underestimate.

(*c*) A SYNTHESIS BETWEEN VIERORDT'S LAW OF THE RELATION OF THE SPACE-THRESHOLD TO THE MOBILITY OF THE PART AND THE LAW OF TACTUAL ESTIMATION OF DISTANCES

Vierordt's law[2] states that the more mobile the part of the body is, the smaller is the threshold. This means in terms of my law: The more mobile the part, *i. e.*, the more the

[1] Fitt, 'Grössenauffassung, etc.,' p. 441 ff. and p. 445.

[2] Vierordt, in *Zeitschrift für Biologie*, VI., 1870, pp. 53–72.

part is and can be used, the higher does the estimation of distances rise towards or in the zone of overestimation. Thus those parts which are of most importance in measuring distances tend towards exaggeration of the magnitudes.

(*d*) Biological Significance of the Law. Different Degrees of Adaptation of the Various Parts of the Skin According to Mobility or Use

Since the sense of touch cannot alone give the same fulness of knowledge of the external world as, *e. g.*, sight, it is natural to expect some adaptation bringing compensation with it. The means of adaptation is the different degrees of pressure-sight coördination. The adaptive compensation is the ability to exaggerate magnitudes, thus to get a very vivid impression from external objects, this ability increasing with the need of adaptation to this mode of measuring.

The tip of the tongue, which has the smallest threshold, has undoubtedly the most vital decisions to make concerning the size, shape, etc., of very minute objects received into the mouth. How usefu it is biologically that a tremendous overestimation should take place! Then again how vital are many of the decisions to be made in the dark through the knowledge gained from the finger-tips!

Thus from the point of view of evolution, through usage in the life of the race the various parts of the skin have become differentiated in regard to accuracy of estimation from what was once almost certainly a general underestimation to the state of the present variable law.

III. (*a*) The Experiments with Boys; the Development of the Tactual Estimation from the Age of 6 Years to the Adult Stage

The experiments with the Grahamstown boys (white) were conducted in the years 1914 and 1915 and those with the German boys in the year 1913 in the Institute for Experimental Pedagogy in the University of Leipzig. Of the former there were 5 boys of 6 years, 4 of 8 years, 4 of 10 years, 5 of 12 years, and 4 of 14 years (total 22) and of the latter 4 of

10 years and 4 of 14 years. As complete results as possible were obtained from the 6-, 10- and 14-year-old Grahamstown boys, but from the 8- and 12-year-olds only some test results to verify or modify (if necessary) the general tendency in the development. The results from the German boys are complete, but with only 2 stages in the development, alone they are of little or no use. They prove particularly interesting, however, when compared with the other more complete series.

The tables which now follow present the complete results for the Grahamstown 6-, 10- and 14-year-olds, first the individual results, then the averages to be compared with the averages for adults. It must be remarked here that the boys were in every case chosen merely at random, so that one should hope to expect a fairly average result for each age, without of course any certainty of the most general results. It has cost much labor and time to obtain this material, and further there is no indication that a greater number of observers was necessary.

TABLE III

6-YEAR-OLD BOYS

Skin-locality	Sp.-Thr.	N	A	Error %	M_o	M_u	M	E_o	r_o	E_u	r_u	Obs.
1. Forefinger.....		10	8.6	+14	5.00	3.16	4.18	11	8.7	7	8.5	B.
		10	9.7	+ 3	2.25	3.16	2.75	11	9.9	8	9.5	M.
		10	7.9	+21	9.02	5.35	7.42	12	7.9	6	7.9	R.
		10	8	+20	5.46	4.54	5.03	10	8.1	6	7.9	S.
		10	7.5	+25	3.16	3.16	3.32	10	8.5	5	6.5	Wb.
2. Cushions of hand.		15	19.66	−31.1	3.94	2.83	3.44	22	19.8	18	19.5	B.
		15	16.66	−11.1	2.63	4.25	3.53	18	16.8	14	16.5	M.
		15	15.83	− 6.2	1.25	2.83	2.21	17	16.2	14	15.5	R.
		15	16.5	−10	1.71	3.68	2.89	18	16.8	14	16.2	S.
		15	14.66	+ 2.2	4.25	1.25	3.62	19	16.5	12	12.8	Wb.
3. Back of hand....		15	20.2	−34.5	6.13	3.30	4.91	24	20.2	19	20.2	B.
		15	21.33	−42.2	2.83	5.32	4.26	23	21.5	18	21.2	M.
		15	20.33	−35.5	0	4.92	3.49	21	20.5	17	20.2	R.
		15	19	−26.7								S.
		15	19.66	−31.1	4.86	2.83	4.52	24	21.8	16	17.5	Wb.
4. Forearm.....		20	40	−83.3								
		15	25									B.
		20	32	−66.66								
		15	26									M.
		20	68	−240								R.
		20	38	−115								
		15	36									S.
		15	26	−61.7								
		20	30									Wb.

TABLE IV

10-YEAR-OLD BOYS

Skin-locality	Sp.-thr.	N	A	Error Per Cent.	M_o	M_u	M	E_o	r_o	E_u	r_u	Obs.
1. Forefinger.....	1.38	10	11.4	− 14	4.40	3.16	3.94	14	12.3	9	10.5	H.
	1.5	10	9.1	+ 9	2.65	5.56	4.43	11	9.9	6	8.3	Th.
	2.25	10	7.5	+ 25	1.85	1.85	1.95	9	8.1	6	6.9	Tr.
		10	13.5	− 35	5.66	7.75	6.86	17	14.5	9	12.5	Ws.
2. Cushions of hand	8.25	15	20.7	− 38	3.32	9.70	7.57	24	22.9	14	18.5	H.
	4	15	20.3	− 35.3	6.71	5.38	6.16	24	21.3	17	19.3	Th.
	6	15	17.7	− 18	4.40	9.35	7.33	20	18.3	13	17.1	Tr.
		15	27.6	− 84	6.71	5.16	6.22	32	29.3	24	25.9	Ws.
3. Back of hand...	14	15	29.7	− 98	8.83	9.33	9.26	35	31.5	24	27.9	H.
	13	15	23.5	− 56.7	6.55	8.91	7.91	27	24.7	19	22.3	Th.
	12.5	22	27.8	− 26.4	5.48	9.24	7.63	31	28.5	23	27.1	Tr.
		15	24.5	− 63.3	8.21	10.29	9.38	29	25.7	19	23.3	Ws.
4. Forearm.....	29	10	41.66	−316.7	20.98	10.88	17.53	58	47	32	36.3	H.
		10	45	−350								Th.
	33.5	22	61.33	−178.8	22.25	20.59	21.44	74	61.7	50	61	Tr.
		22	67.33	−206	25.14	24.71	25.19	82	71	52	63.7	Ws.

TABLE V

14-YEAR-OLD BOYS

Skin-locality	Sp.-thr.	N	A	Error Per Cent.	M_o	M_u	M	E_o	r_o	E_u	r_u	Obs.
1. Forefinger.....	1.92	14	14.75	− 5.3	8.20	8.49	8.44	19	16	10	13.5	Bo.
	1.75	14	16	− 14.3	5.68	10.40	11.94	19	17	11	15	Br.
	1.38	14	12.92	+ 8.4	5.05	3.74	4.66	16	14.3	10	11.5	P.
	1.5	14	9.6	+ 31.4	8.40	1.90	6.32	15	11.3	7	7.9	Ts.
2. Cushions of hand	6	15	20.63	− 37.5	4.92	7.05	6.23	24	22	16	19.25	Bo.
	6.5	32	48.1	− 50.3	6.08	8.25	7.79	53	50.7	42	45.5	Br.
	6.75	32	31.4	+ 1.9	6.40	6.00	6.49	36	33.3	27	29.5	P.
	6.75	32	33.5	− 4.7	7.28	9.09	8.43	38	35.3	28	31.7	Ts.
3. Back of hand...	14.7	28	33.75	− 20.5	5.58	10.08	8.39	38	35.75	27	31.75	Bo.
	15.83	15	45.5	−203.3	9.06	14.56	12.29	51	47.5	36	43.5	Br.
	16	28	28	0	9.00	7.20	8.42	34	30.1	23	25.9	P.
	16.25	28	36.7	− 31.1	6.85	7.26	7.24	41	38.3	32	35.1	Ts.
4. Forearm.....	23.7	20	52.6	−163	15.98	22.27	19.45	60	54.2	42	51	Bo.
	23.7	20	71.8	−259	14.95	38.91	29.57	80	74.2	52	69.4	Br.
	23.5	40	60.4	− 51	20.25	23.28	22.22	72	64.6	48	56.2	P.
	29	20	44.4	−122	18.33	25.94	22.93	56	49	30	39.8	Ts.

On glancing at Table VI, one is struck immediately by the fact that the general law holds definitely for each age, *i. e.*, each part of the skin has its own law of estimation and the relative order of the various points is well maintained throughout.

TABLE VI

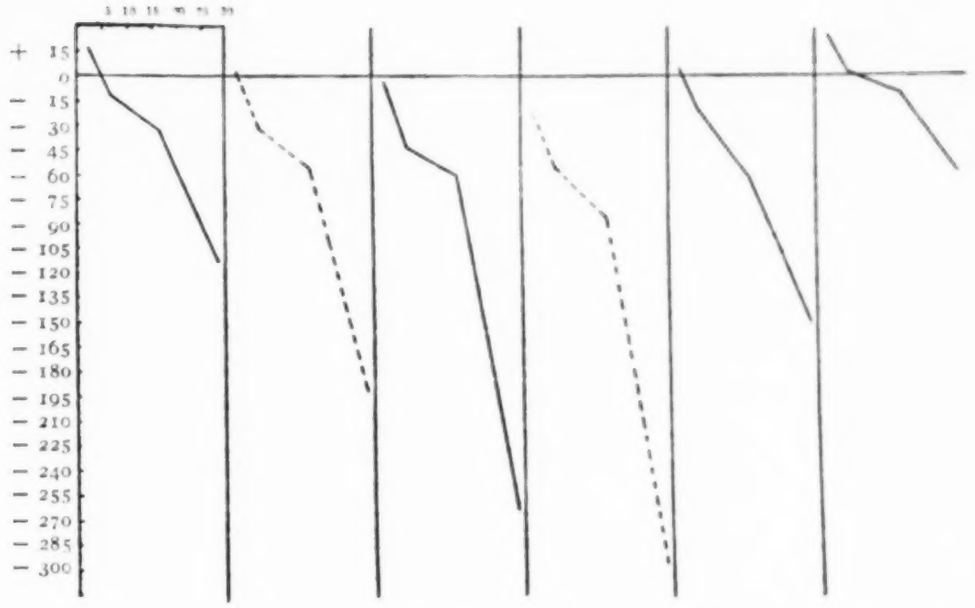
AVERAGES FOR BOYS AND ADULTS

Skin-locality	Space-threshold	Error Per Cent.	M_o	M_u	M	Age
1. Forefinger		+ 16.6	4.98	3.87	4.54	6 years
2. Cushions of hand		− 11.2	2.76	2.97	3.14	
3. Back of hand		− 34.0	3.46	4.09	4.30	
4. Forearm		−113.3				
1. Forefinger	1.7	− 3.75	3.64	4.58	4.30	10 years
2. Cushions of hand	6.1	− 43.8	5.29	7.40	6.82	
3. Back of hand	13.2	− 61.1	7.27	9.44	8.55	
4. Forearm	31.25	−262.9	22.79	18.73	21.39	
1. Forefinger	1.64	+ 5	7.51	6.13	7.84	14 years
2. Cushions of hand	6.5	− 22.7	6.17	7.60	7.24	
3. Back of hand	15.7	− 63.7	7.62	9.78	9.09	
4. Forearm	25	−148.8	17.35	27.60	23.54	
1. Forefinger	2.23	+ 25.2	4.11	3.70	4.24	Adults
2. Cushions of hand	6.83	+ 1.8	4.62	4.87	5.02	
3. Back of hand	16.83	− 10.3	8.73	8.40	8.82	
4. Forearm	28.6	− 58.8	15.40	21.75	19.30	

The first point of difference is that the estimation-curves are differently situated round the indifference-point. It is remarkable that the 6-year-olds (not long entered school) estimate almost as the adults do, although in terms of the general evolutionary interpretation outlined above[1] still somewhat below their level. The whole curve is much longer and much more in the minus-zone than the adult curve. See curves 1, 3, 5 and 6 which correspond to Table VI.[2] From the 6-year-olds to the 12-year-olds, instead of a rise, there is a fall in the estimation curve. Then it rises in the case of the 14-year-olds, although not up to the level of the 6-year-olds, for the 14-year curve is slightly longer and each point lies below the corresponding point in the 6-year curve. The further rise to the adult curve is considerable. So regularly do the four points in the curves rise and fall that the position of any one point, once determined, roughly fixes the position of the whole curve. The investigator, on throwing the results together and finding that the development was a broken one, wished to pursue the investigation further, to the extent of

[1] P. 269.

[2] P. 273.



Curve 1, 6 yrs. Curve 2, 8 yrs. Curve 3, 10 yrs. Curve 4, 12 yrs. Curve 5, 14 yrs. Curve 6, Adults.

The abscissæ represent the space-threshold values and the ordinates the error per cent. + indicates exaggeration and − underestimation.

testing the intermediate periods at the 8- and 12-year-old stages. Values were found for one part of the skin, 'cushions of hand,' and from these proportionate curves (curves 2 and 4) were drawn. There is a high degree of probability that these curves represent the approximate estimation at these two stages. The estimation values for the part ('cushions') are:

8-Yr.-Olds. $N = 15$				12-Yr.-Olds. $N = 15$				
A-values				*A*-values				
Obs. *A*	*B*	*C*	*D*	Obs. *A*	*B*	*C*	*D*	*E*
20.5	16.5	22	20.5	24	21.5	21	21.5	29
Average 19.9 = Error per cent. − 32.7				Average 23.4 = Error per cent. − 56				

The test shows that the estimation for this part of the skin with the 8-year-olds lies in an intermediate position between the corresponding ones with the 6- and 10-year-olds and on the falling grade. The 12-year-old value lies below the 10 year one, so that the rise to the upgrade has not yet commenced. A glance at the curves would suggest some-

where about 13 years as the turning-point for the change upward. The rates of falling and rising are very different. The fall for each period of 2 years from the 6- to the 12-year-olds is slight and practically equal, but the rise is rapid, and particularly so from the changing point to the 14-year stage.

A study of the averages for the various ages has thus shown a regular development. This is demonstrated just as clearly when one compares the individual cases. That the 6-year-olds certainly show a more advanced development than the adults is demonstrated by the fact that the most advanced 6-year-old, Wb., presents a curve practically the same as the average adult curve.

Wb.	+25	+2.2	−31.1	−61.7
Adults	+25.2	+1.8	−10.3	−58.8

Wb.'s curve does not stand nearly as high, however, as several of the most advanced individual adult curves, *e. g.*, Kr., Pc., etc.

The devolution from the 6- to 10-year-olds is demonstrated in the fact that two of the latter show underestimation for all parts of the skin (and even a great underestimation for the first part, forefinger), this occurring in none of the 6-year cases. One sees it further in the great degree of underestimation for the forearm in all 10-year cases as compared with the much smaller minus-values for the same part in the 6-year cases.

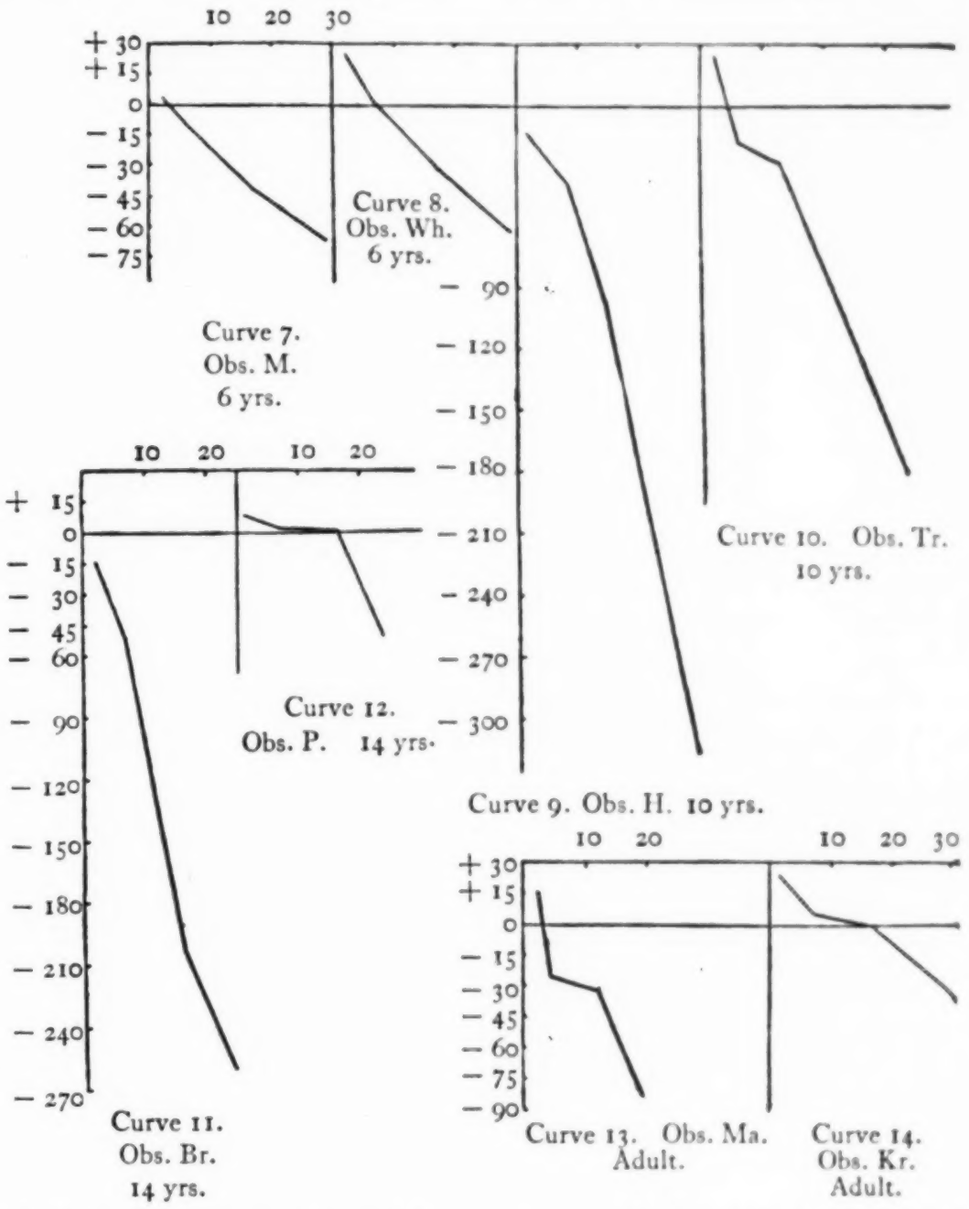
One sees the distinct advance from the 10-year to 14-year-olds in the fact that two of the latter, P. and Ts., present considerably more advanced curves than the most advanced of the former, Tr.

14 yrs.	P.	+ 8.4	+1.9	0	− 51
	Ts.	+31.4	−4.7	−31.1	−122
10 yrs.	Tr.	+25	−18	−26.4	−178.8

The least advanced cases in these two groups, Ws. and Br., are practically the same.

Although the 14-year average is far behind the adult average, and further two of the 14-year individuals, Br. and Bo., show a minus-value for the forefinger (and correspondingly

large minus-values for the other parts) which occurs in no adult case, still it is interesting to note the advanced 14-year case



of P. which is comparable to some of the advanced adult cases, *e. g.*, Kr. and Kn.

14 yrs.	P.	+ 8.4	+1.9	0	−51
Adults	Kr.	+22.8	+4.7	−0.6	−39.8
	Kn.	+37.2	−5.3	−1.1	−22.9

Possibly P. is already advanced as far as he will go in the scale of estimation.

Clearly the average 14-year case has not yet reached the level of the average 6-year-olds. The two backward 14-year

cases of Bo. and Br. lie apparently at about the point of minimal development, *i. e.*, at the turning-point from devolution to advance or very little above it.

In order to illustrate this development through the individual results, curves 7–14 are given, representing the least and the most advanced case for each period (as far as it is possible to choose so definitely).

The Precision-Values

An explanatory remark concerning the M_0-, M_u- and M-values for the 6-year-olds is necessary here. They are very small and this is possibly partly accounted for by the fact that as a rule not as many rows of the variable stimulus for each A-value were given as with the other observers. This was found necessary in order to keep the interest and hence effort in the experiments from flagging. Still it was not considered detrimental to the general results, for the experimenter soon saw from the smallness of the decision-times and the general readiness and ease in the decisions that the precision-values were particularly high. This was not so in the experiments with the fourth group (forearm) where the judgments came with such difficulty that it was considered unwise to attempt full rows of the variable stimulus. Hence the results for this group were obtained from several judgments for distances lying differently about the A-point, without however sufficient data to determine r- and E-values. The above procedure of giving fewer rows of the touch-stimulus had to be adopted occasionally in the experiments with the older boys, but there is no indication of smaller M-values than would otherwise have been obtained. Thus from every indication one can safely state that the precision-values for the 6-year-olds (except for the forearm) are comparatively high, *i. e.*, that the judgments are relatively certain.

There is a clear rise in all the M-values from the 10- to the 14-year-olds, *i. e.*, a fall in the precision. Just as clear too is the rise in the precision from the 14-year-olds to the adults.

Thus there is most probably, if not a fall, from the precision-values of the 6-year-olds to those of the 10-year-olds, at least

no rise. Then there is a fall in the 10–14 years period with a rise to the adult stage. We see here an analogous development to that of the estimation, with a devolution to a certain point, and then a rise to the adult stage. The point where this change to the rise occurs is, however, different in each case. Whereas the estimation-curves rise at about 13 years, the precision-values rise after 14 years. The relation of these two facts will be discussed later. This development of the precision is shown in the following table. The value given for each age is the average struck from the *h*-values (precision-values) for the 4 parts of the skin. This is quite allowable, since the *h*-values for the 4 parts lie in a definite relation to one another.

TABLE VII

$$h = \frac{I}{M\sqrt{2}}.$$

	10 Years	14 Years	Adults
h-values	.07	.06	.08
M-values	10.27	11.93	9.35

The Space-Threshold Values

It is generally assumed that the space-thresholds are smaller with children than with adults, and increase gradually with the age. Our previous investigation established the fact that the actual individual differences in size of the thresholds do not influence the general law of estimation, hence it is practically immaterial here to have the values of the thresholds for the various groups of boys. However, as far as possible, they have been taken, and given in the above tables. The usual procedure for children was adopted here, the procedure of making the end-points in the ascending and descending series 'two-point' and 'one-point' perceptions respectively, and not 'two-point' and 'no longer distinctly two points' as with the adults. This naturally gives slightly smaller results than would be obtained on the adult procedure, and thus the thresholds of the adults and boys are not really comparable. Even with this simpler procedure, much difficulty was found in obtaining satisfactory results, and with the 6-year-olds the

attempt to obtain anything consistent had to be abandoned. Thus the threshold-values for the boys are incomparable with those of the adults both on account of the difference in methodical procedure and also because of their greater uncertainty. For these reasons all curves for averages have as their abscissæ the same threshold-values, those of the adults. As has been shown, this does not affect the general law.

(*b*) The Significance of this Development

These investigations with the boys give considerable support to the general theory of the evolution of the estimation as outlined above. According to this, there appears from the sixth to about the thirteenth year a diminution in the liveliness of the touch-impressions, and at the same time a breaking-down of the coördination between touch and sight, followed by a rapid building-up of this coördination. From the point of view of adaptation we see a fall from the 6-year curve to the 10-year one, the fall continuing to about the thirteenth year, when a rapid regaining sets in, the adult stage showing the highest degree of adaptation. The 6-year curve shows a fair portion above the indifference line, *i. e.*, a relatively close approximation to correct estimation by many parts, with exaggeration by the most sensitive surfaces. The adaptation at 10 years is poor, for all parts show underestimation, which is very considerable with the least sensitive surfaces.

One can hardly resist the suggestion that the breaking-down of the touch-sight coördination is due to the nature of the mental activities of school-life; to the sudden change from the incessant handling and seeing of infancy to the comparative cessation of this and the substitution of a greater activity in abstraction. That this breaking-down does not continue beyond somewhere about the thirteenth year suggests the influence of a new factor. The most likely one is the pubertal change which in many activities is a reinforcing and accelerating factor. It seems natural that the arrest in coördination should not be allowed to continue beyond this vitally important period, and that a rapid building-up should commence. The

thirteenth year is most probably with South African boys on the average the commencing year for the pubertal changes. No very exact statistics for this fact are available, but one may almost assume it from the fact that the average year for English boys is about the fourteenth and that a warmer climate as a general rule means earlier pubescence. The main point for this investigation is the fact that the 14-year-old boys who acted as observers were found to be in every respect some distance on in the pubertal changes and not merely commencing.

From the point of view of sense-development the breaking-down of the coördination, caused almost certainly by school-entrance, is a criticism of the tendencies of modern school-life. It also strongly supports some of the newer types of educational institutions, *e. g.*, the Montessori and manual-training schools.

A breaking-down in the touch-sight coördination would tend to bring about a fall in the precision in the tactual estimation of distances. Were this the only factor involved in the precision one would expect to find exactly parallel developments of the two. Of course there are many factors, one of them being of outstanding importance, the increase or decrease of the general capacity for concentration apart from any specific reference to the nature of the judgment itself. The numerous investigations on the pubertal change incline one to the view that the early stages of puberty are unfavorable to a high degree of precision in the judgment-process. With this fact in mind, one can see considerable parallelism between the development of the estimation and the degree of precision. In the latter there is strong indication of a fall to the fourteenth year (and beyond?), in the former a decided fall to about the thirteenth year with then a rise in each case to the adult stage. The change from devolution to advance has been attributed in each case to the same factor, the pubertal change.

The author wishes to draw special attention to the comparatively high degree of precision with the 6-year-olds. This he attributes to the fact that the boys, living very much in the world of sense, give their decisions frankly and freely, without the scruples which the higher thought-process is liable to

bring. As well, of course, the close touch-sight coördination plays its part.

Experiments with German Boys

For purposes of comparison, and if possible, verification of the generalizations above arrived at, the experiments conducted with the German boys will be given here. The results of Table X. (averages for 10- and 14-year-olds compared with adult averages) are represented in Curves 15, 16 and 17, Curve 17 being Curve 6 reproduced for ease of comparison.

TABLE VIII

10-YEAR-OLD BOYS

Skin-locality	Sp.-thr.	N	A	Error Per Cent.	M_o	M_u	M	E_o	r_o	E_u	r_u	Obs.
1. Forefinger....	1.9	14	9.33	+ 33.3	6.83	3.24	5.72	14	11.33	6	7.33	S.
	2.8	14	12.83	+ 8.4	4.00	5.44	5.06	16	14.5	9	11.17	B.
	2.1	14	13.16	+ 6.0	4.41	5.12	4.92	16	14.33	10	12.0	J.
	2.2	14	11.58	+ 17.3	6.23	8.83	7.64	14	11.67	8	11.5	F.
2. Cushions of hand.....	4.9	32	30.92	+ 3.4	5.79	7.16	6.79	35	32.83	26	29.0	S.
	7.8	32	32.42	− 1.3	6.54	8.84	8.11	38	35.67	26	29.17	B.
	3.2	32	33.00	− 3.1	7.96	6.24	8.05	40	36.7	27	29.3	J.
	7.8	32	33.40	− 4.4	6.16	7.31	6.76	36	33.5	30	33.3	F.
3. Back of hand.	10.7	45	47.58	− 5.7	9.70	11.92	11.25	54	50.5	40	44.67	S.
	18.2	45	49.75	− 10.6	13.78	13.61	14.0	57	52.5	42	47.0	B.
	21.0	38	41.50	− 9.2	11.15	10.40	11.0	48	44.0	35	39.0	J.
	14.0	45	47.50	− 5.6	10.30	10.30	10.30	51	47.5	44	47.5	F.
4. Forearm.....	17.4	40	60.67	− 51.7	32.32	51.80	43.6	78	67	34	54.33	S.
	35.0	40	53.60	− 34.0	18.82	27.14	23.9	66	58.6	38	48.6	B.
	27.3	40	46.00	− 15.0	33.58	11.63	26.3	68	53.8	34	38.2	J.
	23.0	40	61.00	− 52.5	22.80	29.53	26.4	70	61.0	48	06.1	F.

A first glance at these results certainly does not convince one of their similarity to the previous ones as regards development. One is struck first by the shortness of the curves for the 10- and 14-year-olds as compared with the adult curve. Then one finds no such thing as a great rise from the 10-year to the 14-year curve, but rather a suggestion of a slight fall. On looking more closely however, and bearing in mind the different age of the pubertal changes and the very different conditions of life, in school and out of school, one begins to see similarities. Both 10- and 14-year-olds exaggerate with

TABLE IX

14-YEAR-OLD BOYS

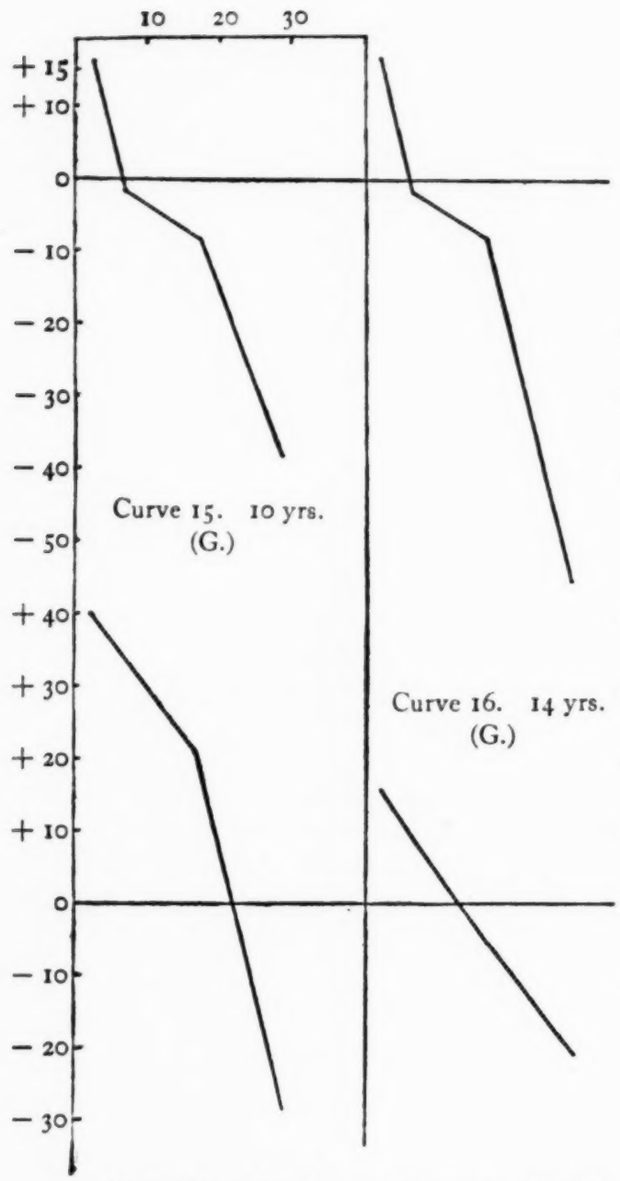
Skin-locality	Sp.-thr.	N	A	Error Per Cent.	M	M_m	M	E_o	r_o	E_m	r_m	Obs.
1. Forefinger....	2.1	14	8.88	+ 36.6	4.79	4.41	4.77	12	10.17	6	7.7	Lö.
	2.0	14	12.17	+ 13.1	6.41	4.92	5.84	16	13.33	9	11.0	Lu.
	1.9	14	13.0	+ 7.1	4.40	6.08	5.46	16	14.3	9	11.7	Lr.
	2.0	14	12.6	+ 10.0	5.74	5.66	5.83	16	13.7	9	11.5	K.
2. Cushions of hand.....	6.8	32	29.08	+ 9.1	10.21	6.90	8.92	35	31.0	25	27.17	Lö.
	9.0	32	33.92	− 6.0	4.52	10.34	8.17	37	35.67	28	32.17	Lu.
	6.8	32	34.8	− 8.8	6.71	5.74	6.42	39	36.3	31	33.3	Lr.
	7.2	32	32.2	− 0.6	5.42	5.28	6.2	37	35.3	27	29.1	K.
3. Back of hand.	13.9	45	46.5	− 3.3	12.01	11.33	12.2	54	50.0	39	43.0	Lö.
	20.0	45	48.5	− 7.8	9.23	21.18	16.5	54	50.67	38	46.33	Lu.
	16.3	45	52.1	− 15.8	12.01	10.07	11.3	59	54.1	46	50.1	Lr.
	11.9	45	47.8	− 6.2	7.87	15.20	12.65	54	51.5	38	44.1	K.
4. Forearm.....	31.4	40	47.0	− 17.5	28.01	13.09	22.3	62	51.33	38	42.67	Lö.
	30.0	40	43.3	− 8.3	13.83	8.00	12.7	52	49.1	36	37.5	Lu.
	34.3	40	61.8	− 54.5	21.41	24.68	23.4	72	65.8	48	57.8	Lr.
	21.7	20	48.4	−142.0	18.83	26.53	23.65	60	53.8	34	43.0	K.

TABLE X

AVERAGES

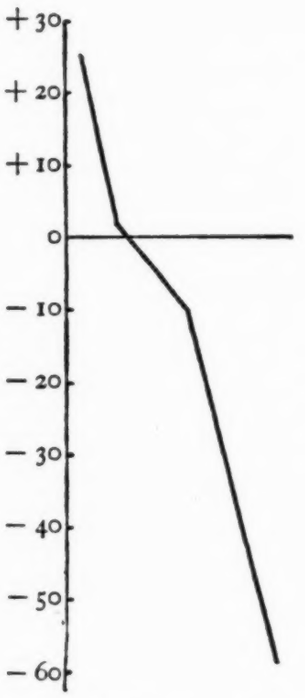
Skin-locality	Sp.-thr.	Error Per Cent.	M_o	M_m	M	
1. Forefinger.....	2.25	+16.25	5.37	5.66	5.84	10 years.
2. Cushions of hand.....	5.93	− 1.35	6.61	7.39	7.43	
3. Back of hand.....	15.98	− 7.8	11.23	11.56	11.64	
4. Forearm.....	25.68	−38.3	26.88	30.03	30.05	
1. Forefinger.....	2.0	+16.7	5.34	5.27	5.48	14 years.
2. Cushions of hand.....	7.45	− 1.6	6.72	7.07	7.14	
3. Back of hand.....	15.53	− 8.3	10.28	14.45	13.16	
4. Forearm.....	29.35	−55.6	20.52	18.08	20.51	
1. Forefinger.....	2.23	+25.2	4.11	3.70	4.24	Adults.
2. Cushions of hand.....	6.83	+ 1.8	4.62	4.87	5.02	
3. Back of hand.....	16.83	−10.3	8.73	8.40	8.82	
4. Forearm.....	28.6	−58.8	15.40	21.75	19.30	

the forefinger, but less than the adults, and underestimate with the three other parts, whereas the adults exaggerate with the cushions of hand. Thus fewer parts of the skin lie above the indifference-point with the boys. This is one of the most important facts of the general law of evolution. Without the results for the 6-year-olds one can hardly see the full meaning of these facts, but the much greater similarity



Curve 15. 10 yrs. (G.)

Curve 16. 14 yrs. (G.)



Curve 17. Adults

Curve 18. Obs. K. 9 yrs.

Curve 19. Obs. H. 14 yrs.

between these three curves than between Curves 1–6 suggests that the change to school conditions does not prove such a contrast to pre-school conditions in the former as in the latter case. My own observations certainly justify this point, for there is no doubt that the change for the Grahamstown boys is very much greater than for the Leipzig boys. The former live a life of considerable activity and freedom in the open air whereas the latter live in a very overcrowded state in big commercial districts. It is quite possible (the different con-

ditions are doubtless very numerous) that the German boys undergo much less change in the estimation than the others, that nature's demand for a high degree of coördination in the period of early childhood is so great that it is attained in any case, and once attained, school conditions fairly closely allied to home conditions produce very little change. However, the main point of the investigation has been verified, the rise in the position of the curve with the adults.

The following table gives the averages for the *M*- and *h*-values (precision-values) for each age.

TABLE XI

	10 Years	14 Years	Adults
h-values	.05	.06	.08
M-values	13.74	11.65	9.35

Here as in Table VII.[1] the precision with the adults is greater than with either of the groups of boys. The fall in the precision from the 10- to the 14-year-olds was explained there by the oncoming of puberty. In this case it rises. The later age for puberty should explain its not falling at this point, but possibly at a later one. This great difference at the 14-year-old stage gives weight to the assumption that puberty was one of the main factors in explaining the change in the estimation.

TABLE XII

Skin-locality	Obs.	Error Per Cent.	M_o	M_m	M
1. Forefinger	K. (9 years)	+40.1	4.9	4.73	4.82
2. Back of hand	K. (9 years)	+20.7	8.84	6.81	7.9
3. Forearm	K. (9 years)	−28.1	14.4	26.34	21.22
1. Forefinger	H. (14 years)	+15.8	4.08	2.65	3.44
2. Back of hand	H. (14 years)	− 5.4	10.48	11.14	10.81
3. Forearm	H. (14 years)	−20.5	24.02	22.78	23.40

It is interesting to refer here to the experiments conducted with the two German boys, H. (14 years) and K. (9 years), brothers attending the same school, already published in the

[1] P. 277.

earlier investigation.[1] For more direct reference the points most relevant to the present discussion will be reproduced here and in curves 18 and 19.

These results are a striking corroboration of the general evolutionary law. The 9-year-old K. stands remarkably high in the estimation scale, showing exaggeration with even the back of the hand. The 14-year-old H. stands about in line with the average German 14-year-old, but exactly whether on the downward grade towards the change-point or on the upward grade beyond this to the adult stage it is not possible to say. The precision-values of .06 (K.), .056 (H.), and .08 (adults), give a very close parallel to those of the Grahamstown boys. K.'s results are undoubtedly very extreme ones for a German boy, judging from the average case.

(*c*) The Estimation of Large Distances, Whose End-Points Lie Near the Edges of Limbs or Other Known Boundaries

In the earlier investigation[2] on this subject, the influence of the magnitude of the distance on the correctness of the estimation was not found to be as great as Henri[3] and Fechner[4] had claimed. Clearly the whole point is such nearness of the points of the æsthesiometer to well-known boundaries as will give appreciable aid to the observer in visualizing the distance and comparing it with the more or less known size of the parts stimulated. Possibly the earlier tests did not employ large enough distances to show this influence, and further there is every likelihood that the observers strove to avoid using the auxiliary associations—they had got into the habit of avoiding all such aids in the process.

With less controlled observers this influence should rather readily show itself. It has been definitely demonstrated in the cases of the 14-year-old Grahamstown boys where a large visual distance of 45 mm. was used for the group 'back of

[1] Fitt, 'Grössenauffassung, etc.,' pp. 448 and 449.

[2] Fitt, 'Grössenauffassung, etc.,' p. 435 ff.

[3] Henri, 'Ueber die Raumwahrnehmung des Tastsinnes,' 1898, p. 61.

[4] Fechner, 'Elemente der Psychophysik,' 1860, II., p. 315 ff.

hand.' Naturally for such a large visual distance many of the touch distances must be considerably greater than 45 mm., and hence lie very near the edges of the hand. These 14-year-olds were the first investigated, and after the influence of large distances had been detected, smaller ones were used and in no succeeding case was there irregularity of this kind. The following table presents the facts.

TABLE XIII

Skin-locality	N	A	Error %	Obs.
Back of hand	28	33.75	− 20.5	Bo.
	45	50.3	− 11.8	
	15	45.5	−203.3	Br.
	45	49.13	− 9.2	
	28	28	0	P.
	45	39	+ 13.3	
	28	36.7	− 31.1	Ts.
	45	45.5	− 1.1	

One observes the same influence throughout. The additional ability to visualize, owing to the nearness of the points of a large distance to the edges of the hand, causes in each case a rise in the scale of estimation for that part of the skin. In three cases, Bo., Br. and Ts., a fairly large underestimation with a relatively small distance changes to a much smaller underestimation with a large distance, and in the case of P. correct estimation changes to overestimation. The effect of the visualizing in the first three cases is the same as the influence which the possession of a strong visual type of imagery has, viz., the estimation is more nearly correct than otherwise would be the case. This has been clearly demonstrated by the author[1] and was also noted by Washburn.[2] This generalization refers, of course, merely to a change from underestimation to more correct estimation, for Washburn's data and mine all bear on this point.

[1] Fitt, 'Grössenauffassung, etc.,' p. 444 ff.

[2] Washburn, 'Ueber den Einfluss der Gesichtsassoziationen, etc.,' in *Phil. Stud.*, XI., 1895, p. 190 ff.

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Fechner's observations on this point have little or no value, owing to his unsatisfactory method and procedure.[1]

Henri finds that underestimation with small distances changes to overestimation with large ones whose end-points approach the sides of the arm. This is really the above change exaggerated and quite similar to the change in the case of P.

In the light of these facts, one must choose distances of such size as to avoid the influence of this factor, which has no relation whatever to the immediate judgment in the tactual estimation.

As a matter of fact the actual judgment becomes complicated by the interference of this new factor, as was brought out in the introspection of the adults.[2] This is well illustrated by the frequency-curves 20, 21, 22 and 23, of Bo. and Ts., showing the disposition of the 'greater,' 'equal' and 'smaller' judgments in the groups represented in Table XIII.

IV. Summary of Main Results

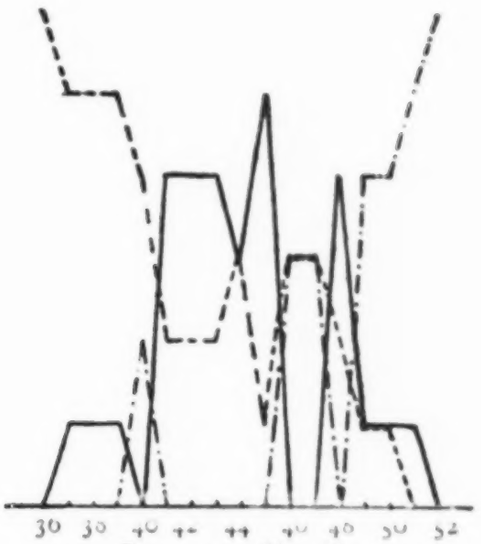
1. (*a*) The general law of tactual estimation with adults: Those parts of the skin which have very small space-thresholds overestimate two-point distances, the overestimation gradually decreasing with increase of the threshold until the indifference-point is reached where the estimation is correct. Increase of the threshold beyond this point brings underestimation, and the greater the increase the greater the underestimation.

(*b*) Its biological significance: The variable law represents different degrees of adaptation of the various parts of the skin according to use. The more mobile the part of the body, *i. e.*, the greater the need of adaptation with the object of completer perception of the external world, the higher the estimation rises in the region of underestimation towards correct estimation or even higher into the region of over-estimation. The concomitant on the psychical side is the gradual increase in the degree of coördination between the pressure experience and the ability to visualize the stimulated part.

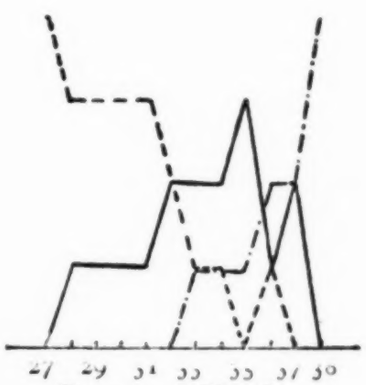
[1] Fitt, 'Grössenauffassung, etc.,' p. 452.

[2] Ibid., p. 445.

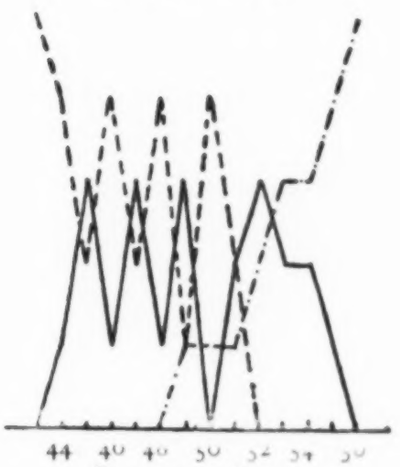
Curve 20. Obs. Ts.
Back of hand; $N = 28$;
$A = 36.7$; $M_0 = 6.85$;
$Mu = 7.26$; $M = 7.24$.



Curve 21. Obs. Ts.
Back of hand; $N = 45$;
$A = 45.5$; $M_0 = 12.17$;
$Mu = 20.23$; $M = 16.9$



Curve 22. Obs. Bo.
Back of hand; $N = 28$;
$A = 33.75$; $M_0 = 5.58$;
$Mu = 10.08$; $M = 8.39$.



Curve 23. Obs. Bo.
Back of hand; $N = 45$;
$A = 50.3$; $M_0 = 8.8$;
$Mu = 13.04$; $M = 11.35$.

"Greater" curve — · — · —
"Smaller" curve - - - - - - - -
"Equal" curve ————

2. The general law holds with boys. With the Grahamstown boys the estimation curve falls gradually from a position at 6 years, where it is only slightly lower than the average adult position, till about 13 years, where the whole curve lies considerably below the indifference-line, *i. e.*, entirely in the

underestimation-zone. Then it rises more rapidly, having crossed the indifference-line by 14 years, where the position is still slightly below the 6-year position and thus lower than the adult position.

3. The fall in the position of the curves from 6 to about 13 years of age represents a breaking-down of the touch-sight coördination due to conditions of school-activity, and the rapid rise after 13 years is attributed to the accelerating influence of puberty.

4. The precision-values of boys in this estimation are smaller than those of the adults. The 6-year-olds show on the whole remarkably high precision-values, corresponding to the frankness and immediacy of their judgments. Hence the possibility of conducting psychophysical experiments with children of this age, provided the mental processes involved are not too complex and that very little be expected on the qualitative side, in the form of direct introspection on their part.

5. Where the tactile distances are large enough to aid estimation through visualization of the stimulated part of the body, what is ordinarily underestimation changes appreciably in the direction of correct estimation, and there are indications that correct estimation or slight underestimation changes to overestimation. This additional visualization causes something of the nature of a divided judgment, appearing in a very irregular and complicated distribution of the 'greater,' 'equal' and 'smaller' decisions.

HAND–TONGUE SPACE PERCEPTION[1]

BY C. N. WATERMAN, JR.

Ohio State University

When the size of a newly formed cavity in the mouth, such as is caused by the removal of a tooth, or other dental work, is explored by the tongue, the cavity seems unusually large. This fact led to the question as to whether areal stimuli on the tongue are overestimated as compared to the same stimuli on the hand. More technically stated, we have the problem:

"What is the relation between tactual space perception on the palm of the hand, and on the tongue, when estimated in terms of visual areas?"

The following apparatus was used. In Fig. 1 is shown an ordinary chair (*A*), across the back of which was fastened the cardboard screen (*a*), extending from the seat to a distance of about eight inches below the presentation frame (*b*). In the screen a hole (*e*) was cut, through which the observer placed his right hand, resting it on the padded crossbar (*d*).

The presentation frame (*b*) was $8'' \times 11'' \times 14''$, painted black on the inside, and fastened to the chair as indicated. At (*c*) an opening was cut through the end and bottom of the presentation frame, so that the observer sitting at (*B*) could conveniently see the visual chart (*C*) which was fastened at (*f*), and yet was prevented from getting a view of anything outside of the frame.

The chart presented at (*f*) is reproduced at (*C*), and consists of a series of twenty-seven circles, the lengths of the circumferences of which varied in steps of .25 cm. starting with a circle .50 cm. in circumference in the center, and ending with a circle 7.00 cm. in circumference at the outside. These were arranged in a spiral pattern, and lettered consecutively from 'A' to '&.'

[1] This experiment was directed by Professor A. P. Weiss, of the department of psychology.

The stimulus rack (*g*) held the set of twelve stimulus rings which were used for both hand and tongue. These consisted of a series of brass tubes, each four inches in length, and of the following circumferences in centimeters: 1.50, 2.00, 2.25, 2.50, 3.00, 3.50, 4.00, 4.25, 4.50, 5.00, 5.50, 6.00. Each was lettered to agree with the circle of corresponding circumference

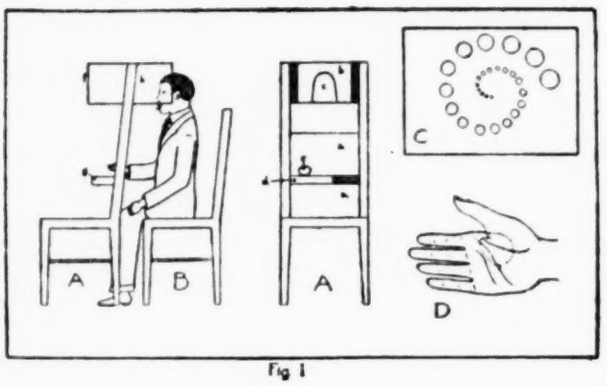
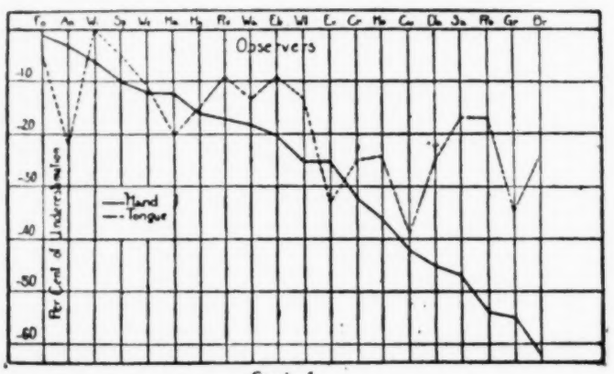
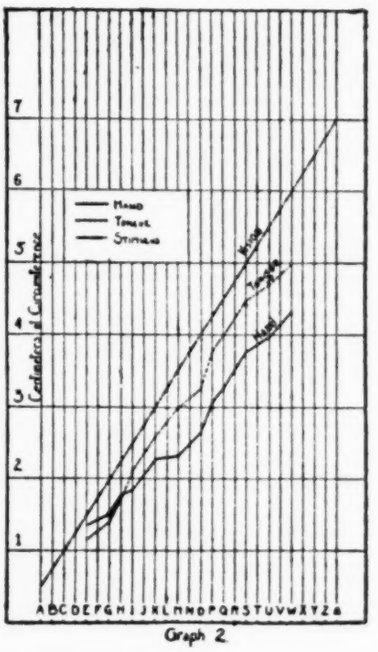


Fig. 1



Graph 1.



Graph 2

on chart (*C*), giving the series E, G, H, I, K, M, O, P, Q, S, U, W. The stimulating edges of these tubes were sharp, but smoothed so that they would not injure the tongue when applied.

When the stimulus was applied to the palm of the hand which the observer had placed through (*e*), the observer estimated and reported which of the circles before his eyes on chart *C* seemed to be the same size as the stimulus on the palm of his hand. The tongue was projected beneath the presentation frame, and the judgments and records were made in the same manner as for the hand.

On the hand, the area stimulated lay within the dotted

line shown on *D*. Upon the tongue, the area stimulated was as near the tip as possible, the stimulus being normal to the surface. This avoided strain in projecting the tongue, but care was taken that it was out sufficiently far to avoid any danger of the teeth being beneath the points stimulated, as this would have prevented uniform contact. Slight movements of the tongue were permitted, though the location of the stimulation ring upon its surface was not changed.

Each series of twelve sizes in random order was presented to the hand and to the tongue. Five of these series, no two of them alike, were presented to the observers, the order being the same for each person. Twelve stimulations of the hand were alternated with twelve stimulations of the tongue, by which procedure fatigue of the end organs was avoided to some extent at least. The full set of ten series (five series of twelve stimulations to the hand, and five to the tongue) occupied about half an hour in presentation. All the time necessary to pronounce a judgment was allowed, and the stimulus was repeated as often as requested.

In computing the data the circumference of the ring was taken as a basis. If the circumference of the stimulation ring is *S* and the circumference of the ring (on chart *C*) which the observer judges to be of equal size is *V*: the per cent. of over- or underestimation was derived by subtracting the circumference of the stimulation ring (*S*) from the circumference of the visual ring (*V*), and dividing the quotient by the circumference of the stimulus ring. Algebraically expressed this gives the formula $V - S/S = E$. For overestimation E is positive, and for underestimation E is negative.

Since there were twelve sizes of rings, each presented five times to the hand and five times to the tongue, the total of the E values for each observer is 120. This gives for each observer the average of sixty judgments for the hand and sixty judgments for the tongue.

The individual results are shown in Table I. Thus, for the observer Fo. the -1 in the first column means that for the hand there was an average underestimation of one per cent. on all the sizes. For the tongue the average underesti-

mation was five per cent. The average deviation for the hand was ±22, and for the tongue ±21. The results of the first two columns of this table are represented graphically in Graph 1. Twenty observers were used.

Results

Table I

Per Cent. of Underestimation

	Average		Av. Deviation	
	Hand	Tongue	Hand	Tongue
Fo	− 1	− 5	22	21
An	− 3	−22	14	13
Wi	− 6	−00	14	13
Sp	−10	− 5	15	10
We	−12	−11	12	11
Ha	−12	−20	17	14
Hy	−16	−15	18	15
Re	−17	− 9	14	12
Wa	−18	−13	11	16
Eb	−20	− 9	10	11
Wil	−25	−13	10	7
Ev	−25	−33	10	11
Cr	−32	−25	11	11
Ho	−36	−24	13	10
Cu	−42	−39	12	18
Da	−45	−25	14	19
Sa	−47	−17	13	15
Ro	−53	−17	8	9
Gr	−55	−35	6	10
Br	−62	−24	9	14
Average	−27	−18	±13	±13

This graph shows the relationship between the estimations of hand and tongue as indicated in the first two columns of Table I. Both hand and tongue areas are underestimated when compared with the visual stimulus. For all but four observers the underestimation of the hand is greater than that of the tongue. The average underestimation of all observers for the hand is 27 per cent.; that of the tongue 18 per cent. Disregarding the absolute underestimation as compared with vision, the overestimation of the tongue as compared with the hand is nine per cent. of the circumference of

the stimulation rings. In other words, the stimulation rings presented to the tongue should be nine per cent. larger than those presented to the hand in order that the two sets may be judged equal. Rather marked individual differences are also shown on this curve.

In Graph 2 the average results of the twenty observers are presented according to the sizes of the stimuli. The dot and dash line gives the circumferences in centimeters of the visual stimuli, represented by their respective letters A, B, C, ····. Thus the circle *A* on the visual chart had a circumference of .50 cm., *B* of .75 cm. and so on. It will be remembered that of the total series of twenty-seven sizes only the following twelve were presented as tactual stimuli: E, G, H, I, K, M, O, P, Q, S, U, W, and on this graph will be found the averages of the *actual* underestimations in centimeters by the hand and tongue for each of these. For example, E has an underestimation of about .125 cm. by the hand and of about .300 cm. by the tongue.

For an explanation of the relatively greater accuracy of the tongue as compared with the hand, the following facts may be of importance. The majority of objects which are placed on the tongue and with which it comes into contact are very nearly the sizes of the stimulation rings, so that judgments made of the tongue stimulation correspond rather closely with the sizes of objects usually placed on the tongue. In other words the tongue judgments were made under the more habitual conditions, and should therefore be expected to be more accurate.

The objects which are judged by the hand, however, are as a rule larger than the stimulation rings. The palm of the hand seldom comes into contact with small objects, and even then hardly ever for the purpose of discrimination. When we wish to feel the size of anything it is moved about between the tips of the fingers. But in the palm of the hand many large and fairly homogeneous surfaces are applied as is illustrated by the grasping of the handle of a hammer, where the whole palm is stimulated equally and at the same time. Since this area is little used for discrimination and the surfaces with

which it does come into contact are large, it is not surprising that its accuracy is less than that of the tongue.

Since the problem is by no means solved by the above investigations, a more detailed and theoretical discussion will be postponed until a number of further experiments are performed. It is desired to test the influence of movement upon the judgment; the relation of the hand judgment to the tongue judgment without the visual medium, and the relationship of judgments carried out by the hand alone, and the tongue alone.

From this experiment, however, it may be stated:

1. Perception of size is more accurate with the tongue than with the hand: underestimation for the tongue 18 per cent., for the hand 27 per cent.

2. The average deviations for both hand and tongue are approximately the same.

3. The individual variations in the estimations of sizes are greater for the hand than for the tongue.

SOME AREAS OF COLOR BLINDNESS OF AN UNUSUAL TYPE IN THE PERIPHERAL RETINA

BY C. E. FERREE AND GERTRUDE RAND
Bryn Mawr College

At the psychophysical section of the first Congress for Experimental Psychology held at Giessen April 18–21, 1904, F. Schumann reported what he termed an unusual case of color blindness (his own).[1] So far as the ability to get the positive sensation is concerned, Dr. Schumann is, according to the report, totally blind to green and partially so to red.[2] In addition his case presents the following features. (1) While green light does not arouse a sensation of green, it does give red after-image and contrast sensations. Red light on the other hand gives a positive sensation but does not give either after-image or contrast sensations.[3] (2) A colorless mixed light can be matched by combining homogeneous red and green lights, but quite a little greater proportion of green is needed to give the neutral sensation than is required for

[1] Schumann, F., 'Ein ungewöhnlicher Fall von Farbenblindheit,' Bericht über den I. Kongress für experimentelle Psychologie in Giessen, 1904, pp. 10–13. See also G. E. Muller's discussion of the report, *ibid.*, pp. 20–21.

[2] His diagnosis that he is partially sensitive to red was based on two facts. (*a*) Red in the region of 670 $\mu\mu$ gave a sensation which was plainly different from yellow and could not be matched by a full spectrum gray. And (2) orange which to the normal eye appeared distinctly reddish, appeared to him a pure yellow. From this point in the orange towards the short wave-length end of the spectrum three qualities were sensed: a yellow, a blue and a band between them which could be matched with a full spectrum gray. On these facts was based the diagnosis of blindness to green.

[3] While a red light does not give green contrast sensation, it does produce an effect on a neighboring field which raises the threshold or diminishes the sensitivity to red. That is, a gray ring on a red ground appears gray but an amount of red can be added to it without being sensed which is supraliminal when red is not present in the surrounding field. In other words a physiological induction seems to be present which inhibits the complementary excitation although the induced excitation does not itself arouse sensation. We have here, therefore, another evidence that the complementary and induction relations between red and green are intact, the ability of the green excitation to arouse sensation alone being absent.

the normal eye. And (3) a yellow of the spectrum can be matched by the combination of a red and green if properly selected. In this case also a considerably greater proportion of green is needed than is required for the normal eye.

One of the writers[1] mentioned several years ago in a partial report of a somewhat extensive investigation of the color sensitivity of the peripheral retina that small areas could be found in the periphery of the normal retina showing characteristics for the colors red, green, yellow and blue similar to the Schumann case for red and green. That is, areas may be found which are totally blind or deficient to one of these colors so far as the positive response is concerned, but which seem not to be correspondingly deficient in the after-image and complementary or cancelling reactions. In fact, so far as can be told, the after-image and complementary reactions are no different in these areas from those in the immediately adjacent normal portions of the retina. We found it infeasible to test for a contrast reaction in these comparatively small and remote areas. Since that time an examination has been made of the eyes of a number of observers, more especially in connection with the work of the undergraduate laboratory, with the result that although observers may differ widely with regard to the number of the spots, their location, and the color responses affected, we are inclined to believe that the presence of such spots in the peripheral retina may be considered the rule rather than the exception.

A successful search of the peripheral retina for spots of the kind described above requires some means of making a rather minute investigation from center to periphery in a number of meridians. In our own work the rotary campimeter has been employed as a means of presenting the light to the different parts of the retina and the investigation has been made both with pigment papers and with the light of the spectrum as stimuli. In case the light of the spectrum was used, a very intensive stimulation was given. The lights were narrow bands taken

[1] Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color,' *Psychol. Rev. Monog.*, 1913, *15*, footnote, pp. 108–109. See also Ferree and Rand, 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Jour. of Psychol.*, 1912, *23*, p. 331.

from the spectrum of a Nernst filament (corrected for impurities) operated by 0.6 ampere of current, and was of the order of intensity at the eye of 11.14×10^{-8} watt per sq. mm. for the red; 9.676×10^{-8} watt per sq. mm. for the yellow; 1.285×10^{-8} watt per sq. mm. for the green; and 0.878×10^{-8} watt per sq. mm. for the blue. The total amount of light entering the eye was in each case respectively 36.76×10^{-8} watt; 31.93×10^{-8} watt; 4.24×10^{-8} watt; and 2.90×10^{-8} watt. Lights of this intensity for the same observers were sufficiently strong, for example, to be sensed as color clear out to the limits of white light vision for all the colors but the green; and the green, it may be mentioned, could not for the observers used be made to coincide with the limits of white light vision whatever intensity of light was employed. The only effect of these greater intensities was to narrow in some cases the area of the spots previously mapped by means of the pigment paper stimuli. Thus it seems that the totally blind area is frequently bounded by a zone of weakened sensitivity. The investigation was made with three conditions of surrounding field: a gray of the brightness of the color, white and black. The only effect of the white and black surrounding fields was to increase the size of a spot mapped with a surrounding field of the gray of the brightness of the color. A preëxposure of a gray of the brightness of the color was used in each case. Care was taken to keep the intensity of the illumination of the room accurately constant throughout the investigation.

In testing for the after-image reaction, a few seconds of preëxposure was given to a gray of the brightness of the color previous to the color stimulation. The color stimulation was given for 3 sec. and the after-image projected on a gray of the brightness of the color, placed in the path of the colored light just behind the campimeter-opening. The intensity of after-image was compared as well as could be with that obtained with the same intensity and conditions of stimulation on the immediately adjacent portions of the retina. So far as could be told there was characteristically no difference between the strength of the after-image reaction in the spot itself and in

the immediately surrounding retina. In the investigation of the complementary or cancelling reaction, a combination of the complementary colors to gray was made for the surrounding portions of the retina and this stimulus was presented to the color-blind area. In each case it was seen as gray, not as the color complementary to that for which the spot was blind. We need scarcely point out that in making this test it was necessary to determine whether the amount of colored light employed would have aroused color sensation had it not been combined with its complementary color. This was done in two ways: (*a*) The amount of color used to form the combination to gray was presented to the color-blind area, combined with the proper value of a substitute sector of the gray of the brightness of the color to which the area was blind; and (*b*) the threshold was determined in the color-blind area for the color complementary to that to which the area was blind, and its value compared with the amount used in making the combination to gray. The results of both determinations showed that a true complementary action was present.

The peripheral retina spots while similar in a general way to the case described by Schumann present the following points of difference. (1) There was no detectable weakening of the sensitivity to the complementary or antagonistic color in the areas in question. And (2) no more of the color to which the area was blind was required to combine to gray with the antagonistic or complementary color than was needed on the normal areas of the retina immediately adjacent.

In the presentation of results space will be taken for only two observers, selected because of rather wide differences in the number, size and location of the spots. In Chart I. is shown results for Observer R. and in Chart II. for Observer C. The Hering pigment papers were used as stimuli and the investigation was made with surrounding field and preëxposure of the brightness of the color in each case. The limits of sensitivity were determined for each color in 16 meridians and these points are connected to give outline maps of color sensitivity for stimuli of the intensity used. In working in any of the above-mentioned meridians the stimulation was given at points

separated by no more than 1°. When a gap or a significant depression in sensitivity was found, the campimeter was rotated and the investigation made in a sufficient number of near-lying meridians to give a careful outline of the deficient area. These areas are represented on the charts in black, with letters to indicate the colors to which there is a deficiency. In case there is total blindness to the stimulus used, the spot is repre-

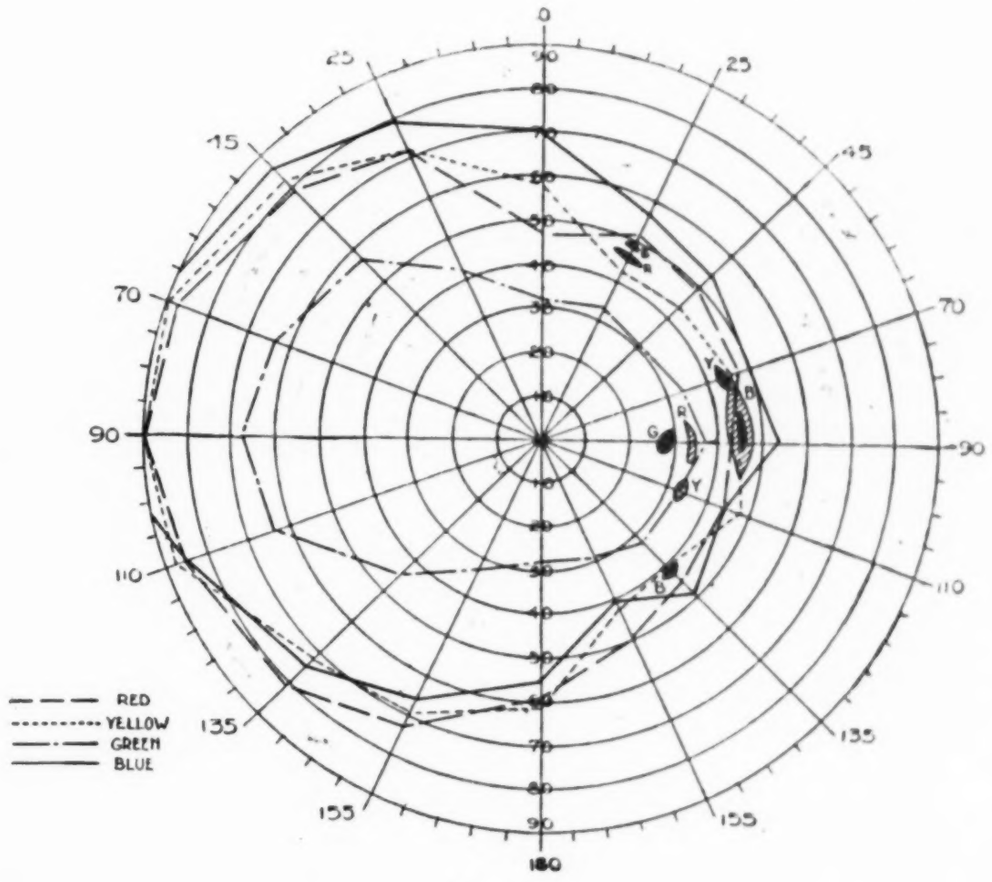


CHART I

Showing for Observer R the Areas of the Peripheral Retina having the Schumann Type of Color Blindness. These areas are represented in black, with letters to indicate the colors to which there is a deficiency. In case there is total blindness to the stimulus used, the area is represented in solid black; in case there is only a marked depression of sensitivity, the area is shaded. In this latter case areas are represented only when the depression amounts nearly to blindness. The only effect of using spectrum lights of very high intensity: red (670 $\mu\mu$), 36.76×10^{-8} watt at pupil of eye; yellow (581 $\mu\mu$), 31.93×10^{-8} watt at pupil of eye; green (522 $\mu\mu$), 4.24×10^{-8} watt at pupil of eye; and blue (471 $\mu\mu$), 2.90×10^{-8} watt at pupil of eye, was to narrow in some cases the area of the spots previously mapped by means of the pigment paper stimuli.

sented in solid black; in case there is only a marked depression of sensitivity the area is shaded. In this latter case areas are represented only when the depression of sensitivity amounts nearly to blindness. They were, for example, so insensitive that the color response could not be aroused when an unfavorable brightness of surrounding field or preëxposure was used.

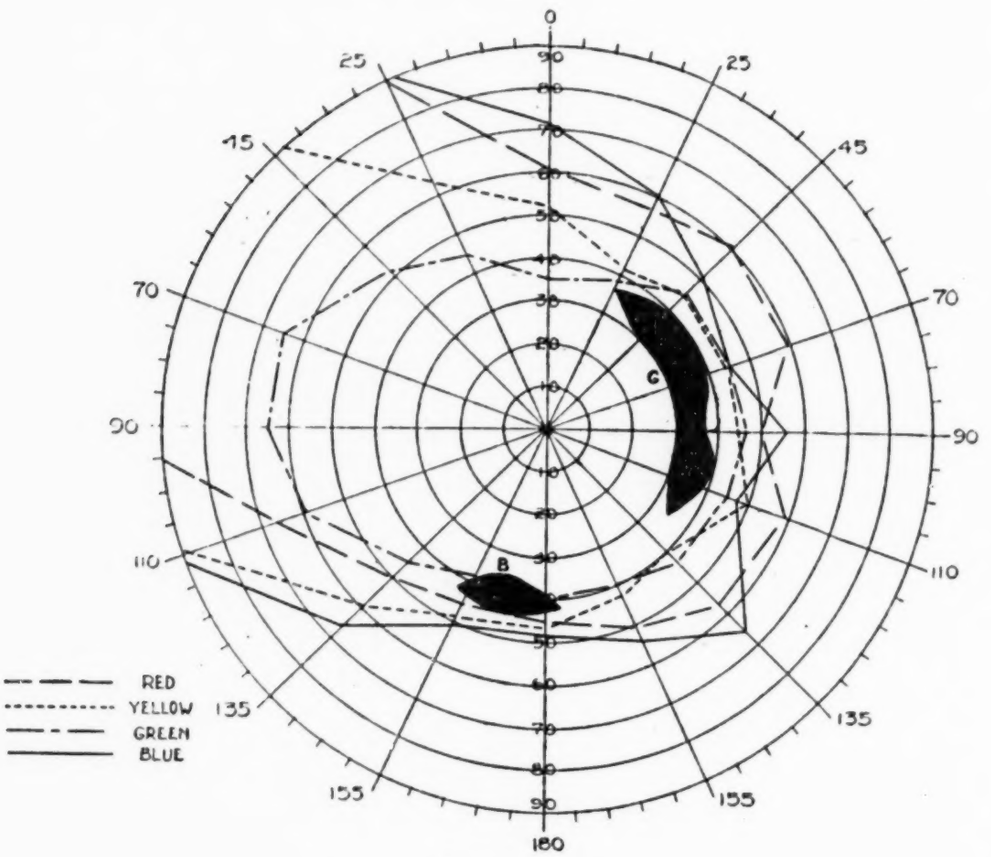


CHART II

Showing for Observer C the Areas of the Peripheral Retina having the Schumann Type of Color Blindness. The conditions of investigation and method of representation is the same in this chart as in Chart I. The results for Observers R and C are selected for presentation here because of the somewhat unusually wide difference that was found in the number, size and location of their spots.

In discussing his own case, Schumann seems to think that the phenomenon indicates that there must be more than one functional level involved in the production of visual sensation: peripheral or sub-cortical, and cortical. One of these, the peripheral or the sub-cortical, is the locus of the complementary or cancelling action, and the after-image and contrast reac-

tions. Green light in his case arouses these three reactions because the level concerned in producing them is functionally normal. Green does not arouse the positive sensation, however, because there is functional deficiency in the remaining level or levels. G. E. Müller, who also made supplementary tests and experiments on Schumann and discussed Schumann's report at the Congress in Giessen, concurs strongly in the conception that more than one functional level is needed to explain the Schumann case. At this same Congress Müller[1] discusses seven types of color-blindness which he further believes can be explained best on the conception of more than one specific functional level, the processes of which may be separately deficient. His theory of color vision is in fact here elaborated to include both peripheral and central visual processes. While we have no wish to engage in theoretical discussions at this stage in our own work, it may not be out of place, in addition to the results presented in this paper, to call to mind in this general connection our experiments of the effect of the achromatic excitation on the chromatic which seemed to indicate very strongly that this effect both quantitative and qualitative takes place at some level posterior to that of the cancelling, after-image, and contrast reactions.[2] We have also obtained other results, as yet unpublished, on contrast induction in the far periphery of the retina which seem to indicate that the deficiency which for these portions of the retina prevents the color stimulation from producing sensation is in part at least posterior to the level at which induction takes place. Moreover, unless the complementary action were intact in case of

[1] Müller, G. E., 'Die Theorie der Gegenfarben und die Farbenblindheit,' Bericht über den 1. Kongress für experimentelle Psychologie in Giessen, 1904, pp. 6–10. The conception of a central deficiency was used as early as 1868 by Niemetschek to explain color blindness (*Prager Vierteljahrschrift, 100*, p. 224).

[2] The results of these experiments have as yet been published only in part. (See "An Experimental Study of the Fusion of Colored and Colorless Light Sensations. The Locus of the Action," *Journ. of Philos., Psychol. and Scientific Methods*, 1911, *8*, pp. 294–297.)

The fuller publication has been delayed for one reason because we have felt the need of giving a somewhat exhaustive résumé of the work that has yet been done on the subject. This work has been so scattered and unsystematic and so much of it appears hidden under titles that give no indication that it is there, that the work of compiling has been somewhat time consuming.

blindness to one color over a whole or part of the retina, it would seem that white light should always be sensed by the subject in the tone complementary to that for which the blindness exists.[1] Or to put the matter more conservatively in terms of color-blindness testing, it would seem impossible ever in such cases to match a full spectrum gray to the color to which the subject is blind, or to all combinations of complementary colors, or to any in fact except the pair to one member of which the defect exists.

In the study of the eye as a recording instrument it is always a helpful feature to take our start from the physical recording instruments which respond to light. Not only are the characteristics of a given one of these instruments more accessible to study than the eye, but the instrument itself can be changed and the effect produced be noted. Also different types of instrument are accessible to study. Just as the simpler work on the study of the physical instruments serves as a helpful methodological guide in the experimental determination of the characteristics of response of the eye, so may we get methodological helps from the study of these instruments which may be of service in forming our conceptions of the actions and functional relations of the cerebro-retinal structure.

One of the characteristics of the instruments which respond to radiant energy is with the exception of the photographic plate a surface or layer in which the energy of the light-wave is transformed into an effect which it is the function of another part of the apparatus to record. This transformation, moreover, in case of some of these instruments: the selenium cell, the photoelectric cell and the photographic plate, is selective;

[1] It is possible that an alternative explanation of the above point may be found in some of the other types of modification of existing theories, *e. g.*, Fick's and Leber's modification of the Helmholtz theory to explain the variations in the color sensitivity of the peripheral retina (see Fick, A., 'Arbeiten aus dem physiol. Laborat. der Würzburger Hochschule,' pp. 213–217; Leber, T., *Klin. Monatsblätter f. Augenheilk.*, 1873, *11*, pp. 467–473). The conception of different functional levels, however, should at least be recognized as one of the possibilities of explanation for monochromatic deficiencies, and as a very plausible and perhaps necessary assumption to explain phenomena of the kind described by Schumann and by the present writers in this paper.

i. e., it is different in amount for the different wave-lengths[1] and the selectiveness varies with the intensity of light used. There is an analogue to this in the selectiveness of the achromatic response of the eye to wave-length and the variation of this selectiveness with change of intensity of light. (In case of the achromatic response this is known as the Purkinje phenomenon.) Some of these instruments also show like the eye a lag in coming to their maximum of response, a fatigue effect, and an after-effect. All of these effects are characteristic of the receiving part of the instrument, not of the recording mechanism. The final form into which the response of the instrument is put is, however, a function of the recording part of the apparatus. Moreover, either one of these parts of the apparatus may, we scarcely need point out, be separately deficient without the impairment of the other. In view of the general similarity in characteristics of response shown between the eye and these instruments, it would not seem entirely unreasonable to suppose,[2] therefore, even in advance of a decisive amount of the evidence which seems to be accumulating, that the visual apparatus consists of receiving and recording parts or levels both of which are necessary to the final response, but either of which may be separately deficient without impairment of the function of the other.

[1] Griffith, I. (*Phil. Mag.*, 1907, *14*, (6), p. 297) working with ultra-violet radiations and Dember, H. (*Ber. d. kgl. sächs. Akad. d. Wiss.*, 1912, *64*, p. 266) working with the visible spectrum both claim that the photoelectric cell is selective in its response to intensity of light. Elster and Geitel (*Phys. Z.*, 1913, *14*, p. 741; 1914, *15*, p. 610) however, found a constant relation between intensity of light and the response of the cell except in case of very intense light. For a fuller discussion of this point see Ferree and Rand, *Psychological Review Monographs*, 1917, XXXII, (5), p. 46.

[2] It will be understood that an analogy between the eye and the physical recording instruments is attempted here primarily as illustrative rather than as argumentative.

THE PROGRESSIVE ERROR OF THE SMEDLEY DYNAMOMETER

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Introduction

There are, undoubtedly, scores of Smedley dynamometers now in actual use in this country. That these instruments may be furnishing inaccurate data, inaccurate to all who may wish to make use of such measurements, has already been intimated by a few. At the present time it would hardly be safe procedure to accept any table of figures at its face value. The reason for this we hope to demonstrate in the present article. When the same amount of pressure yields as much as ten or fifteen pounds difference in the registrations of two different dynamometers, the situation is scientifically serious enough for thoughtful consideration. It is to be regretted that but little space has yet been devoted in the literature of tests to an adequate discussion of errors of instruments. In the meantime we have been accumulating numerous records of dynamometer reactions which, from a rigorously scientific viewpoint, are questionable. Strictly speaking, the machine, following natural laws, is honest. It is the injected human element which makes for error. In the interests, therefore, of accuracy and uniformity this study was undertaken.

Previous Literature: Psychological

Three contributions may here be mentioned.

Wallin in 1912[1] attempted to determine the variability of his instrument and found the following: (1) that the spring was too "stiff"; (2) that as the pressure increased so did the margin of inaccuracy; and (3) that different days (in December and in March) yielded different registrations for the same

[1] 'Experimental Studies of Mental Defectives,' Baltimore: Warwick and York, p. 155.

strain. For the first two conclusions a table of data is published, for the third, however, no figures are presented.

Whipple in 1914[1] advises that the calibrations be checked occasionally to eliminate the possibility of instrumental error.

Mead in 1916[2] used a two-spring Narragansett Machine Company dynamometer. Upon testing his instrument he found that it registered too low. Utilizing one standard weight, 32.5 pounds, his registrations read: 28, 28, 28, 28 when the weight was placed on top. And when hung below, in the 13.5 ounce carriage, the readings were 24, 23, 25, 25.

Previous Literature: Physical

The treatment of the subject in textbooks on mechanics is meager and fragmentary. Here and there one finds mention of the dynamometer as an example of the possible practical application of the laws discussed under the general heading of elasticity. Those who wish further information regarding this phase of the problem may find additional items of interest in the references cited at the end of this article under "Physical Aspects."

The principle underlying the working of the dynamometer is this: Below the elastic limit of a given material (both for compression and extension) the stretch (strain) is proportional to the load (stress) producing it. Presented in another form: elasticity is equal to the stress divided by the strain. And since elasticity is constant for our instrument, the amount of compression will always be proportional to the amount of force applied. The bearing of this important fact upon the recording of dynamometer readings will be made evident in a moment.

Present Series of Tests

On December 28, 1916, between two and three in the afternoon, the Buckel Foundation dynamometer was submitted to

[1] 'Manual of Mental and Physical Tests,' Vol. I., Baltimore: Warwick and York, p. 365.

[2] 'Relations of Intelligence to Mental and Physical Traits,' Columbia University Contributions to Education, No. 76, p. 117.

the following ordeal: After tightening the few screws (front and back) we tied the instrument securely to a horizontal support, with the scale visible and with the outer stirrup nearest the floor. We then threw a rather stout piece of cord (doubled) over the center of the inner stirrup so that the cord hung on both sides of the outer stirrup. There was contact with the cord at these two points, the friction of which we eliminated by thorough greasing. The dangling ends were then knotted, our weights being suspended from that place. In all the trials the weights were very carefully hooked on the cord, thus keeping our measuring force constant. For each trial the weights were removed, the registering dial adjusted at 0 kg., the proper number of weights suspended and the reading taken from the upper or right-hand edge of the dial. The stationary dial was moved out of the way, past the 100 kg. mark.

In the following table are represented the registrations for the different standard weights, beginning with five kilograms. (Visualized in Graph I.)

TABLE I

DYNAMOMETER READINGS PER STANDARD WEIGHT (STANFORD)

Standard Weight (Kg.)	Dynamometer Readings						Average Error	Increment of Error
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average Reading		
5	4.25	4.5	4.5	4.5	4.5	4.45	−0.55	+0.55
10	9.0	9.25	9.5	9.25	9.5	9.30	−0.70	+0.15
15	13.5	14.0	14.0	13.75	14.0	13.85	−1.15	+0.45
20	18.0	18.0	18.0	17.5	18.0	17.90	−2.10	+0.95
25	22.8	22.75	23.0	23.0	22.75	22.86	−2.14	+0.04
30	27.0	27.0	27.0	27.5	28.0	27.30	−2.70	+0.56
35	32.0	32.25	32.2	32.0	32.75	32.24	−2.76	+0.06
40	36.25	36.5	36.75	36.75	36.9	36.63	−3.37	+0.61
Average increment of error								+0.42

We note that the mean increment of error is equal to +0.42 kg. for every 5 kg. of standard weight. And, therefore, the differences between standard weight and dynamometer reading increase, for every 5 kg., in arithmetic progression.

Having ascertained this fact, we may now correct Table I. for errors of observation, yielding Table II.:

TABLE II

TABLE I CORRECTED FOR ERRORS OF OBSERVATION

Stsndard Weight	Dynamometer Reading	Error	Increment of Error
5	4.58	−0.42	+0.42
10	9.16	−0.84	+0.42
15	13.74	−1.26	+0.42
20	18.32	−1.68	+0.42
25	22.90	−2.10	+0.42
30	27.48	−2.52	+0.42
35	32.06	−2.94	+0.42
40	36.64	−3.36	+0.42
45	41.22	−3.78	+0.42
50	45.80	−4.20	+0.42
55	50.38	−4.62	+0.42
60	54.96	−5.04	+0.42

Error index = 0.916,
Correction constant = 1.09.

The index of error is a constant and is equivalent to the dynamometer reading per standard weight divided by standard weight. Thus in Table II., for the standard weight 5, the dynamometer reading is 4.58. The error index is, therefore, equal to 4.58/5, or 0.916. This remains constant no matter how small or how large the force exerted upon the instrument.

TABLE III

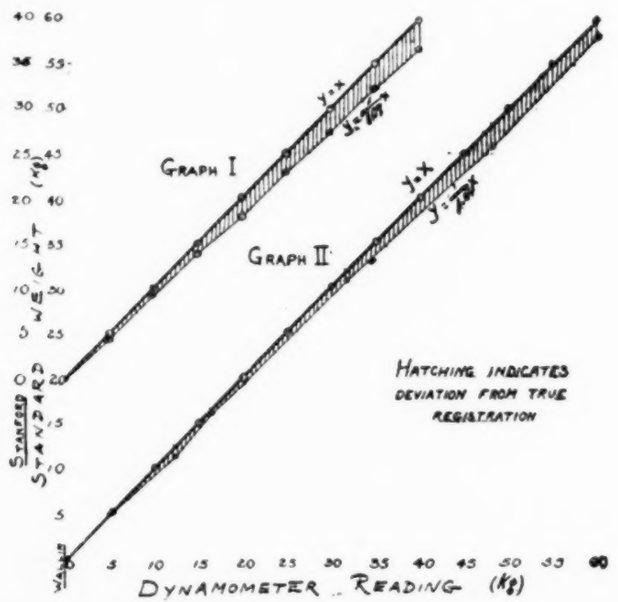
CORRECTIONS FOR DYNAMOMETER READINGS OF TABLE II

Dynamometer Reading (Kg.)	Positive Correction (Kg.)	Dynamometer Reading (Kg.)	Positive Correction (Kg.)
5	+0.45	45	+4.05
10	+0.90	50	+4.50
15	+1.35	55	+4.95
20	+1.80	60	+5.40
25	+2.25	65	+5.85
30	+2.70	70	+6.30
35	+3.15	75	+6.75
40	+3.60	80	+7.20

We may also obtain a correction constant by dividing the standard weight by its dynamometer reading. Thus in Table II. for the standard weight 10 the dynamometer reading is 9.16. To obtain the correction constant, 10 is divided by 9.16, yielding a quotient of 1.09. This factor remains constant no matter what the effort exerted. Thus a reading of 16 kg. really signifies the exertion, on the part of the subject, of 17.44 kg. of effort (16 kg. × 1.09 = 17.44 kg.). And a reading of 57.5 kg. really signifies the exertion of 62.7 kg. of

effort. A difference between the two, in the first case of 1.44 kg. (3 lbs. $2\frac{3}{4}$ oz.), and in the second of 5.2 kg. (11 lbs. $7\frac{2}{5}$ oz.). The differences certainly are serious enough to emphasize the necessity for correction. In Table III. are noted the corrections for the different dynamometer readings.

It is evident that the numerical value of the correction for each reading is the same as the numerical value of the error, except that one has a positive and the other a negative algebraic sign. To obtain the true force exerted, the correction quantity is added to the dynamometer reading. The amount of error indicates how far the dynamometer falls short of the true registration.



The algebraic expression of the line indicating the condition in which standard weights and dynamometer readings are in agreement is $y = x$ (perfect correlation). Should there be a progressive disagreement, as in our case, the correction constant being 1.09, the above-mentioned algebraic expression becomes $y = \frac{1}{1.09}x$ ("x" standing for dynamometer reading, and "y" for standard weight).

Wallin's Series of Tests

Treating Wallin's data similarly, Table IV. is obtained, in which the registrations per standard weight are recorded. Presented in curve form Graph II. is obtained.

TABLE IV

DYNAMOMETER READINGS PER STANDARD WEIGHT (WALLIN)

Standard Weight	Dynamometer Reading[1]	Error	Increment of Error
5.2	5.2	0	——
12.4	11.7	−0.7	+0.7
16.5	16.4	−0.1	−0.6
31.7	30.6	−1.1	+1.0
48.2	45.7	−2.5	+1.4
60.3	58.2	−2.1	−0.4

[1] Averages based on from 3 to 20 trials per standard weight.

From the readings of Graph II., abscissas and ordinates, Table IV. may be converted into Table V.:

TABLE V

DYNAMOMETER READINGS PER STANDARD WEIGHT (WALLIN)

Standard Weight	Dynamometer Reading	Error	Increment of Error
5	5.0	0	——
10	9.5	−0.5	+0.5
15	14.6	−0.4	−0.1
20	19.5	−0.5	+0.1
25	24.1	−0.9	+0.4
30	28.8	−1.2	+0.3
35	33.6	−1.4	+0.2
40	38.1	−1.9	+0.5
45	42.7	−2.3	+0.4
50	47.5	−2.5	+0.2
55	52.6	−2.4	−0.1
60	57.7	−2.3	−0.1
Average increment of error.....			+0.19

Since the average increment of error is +0.19, we may again state Table V., now corrected for errors of observation. This is done in Table VI.:

TABLE VI

TABLE V CORRECTED FOR ERRORS OF OBSERVATION

Standard Weight	Dynamometer Reading	Error	Increment of Error
5	4.81	−0.19	+0.19
10	9.62	−0.38	+0.19
15	14.43	−0.57	+0.19
20	19.24	−0.76	+0.19
25	24.05	−0.95	+0.19
30	28.86	−1.14	+0.19
35	33.67	−1.33	+0.19
40	38.48	−1.52	+0.19
45	43.29	−1.71	+0.19
50	48.10	−1.90	+0.19
55	52.91	−2.09	+0.19
60	57.72	−2.28	+0.19

Error index = 0.962,
Correction constant = 1.04.

In Table VII. are noted the corrections for the readings of this dynamometer:

TABLE VII

CORRECTIONS FOR DYNAMOMETER READINGS OF TABLE VI

Dynamometer Reading (Kg.)	Positive Correction (Kg.)	Dynamometer Reading (Kg.)	Positive Correction (Kg.)
5	+0.20	45	+1.80
10	+0.40	50	+2.00
15	+0.60	55	+2.20
20	+0.80	60	+2.40
25	+1.00	65	+2.60
30	+1.20	70	+2.80
35	+1.40	75	+3.00
40	+1.60	80	+3.20

A COMPARISON OF THE ACCURACY OF THE TWO DYNAMOMETERS

In comparing Tables III. and VII., it will be apparent that the error of the Stanford dynamometer is slightly more than twice the error of Wallin's instrument. Thus a reagent exerting exactly 50 kg. of force upon both machines would register 45.80 kg. on one (Stanford), and 48.10 kg. on the other (Wallin). Or, stated differently, the same registration of 50 on both machines would signify the exertion of a force equal to 54.50 kg. on the Stanford instrument, and only 52.00 kg. on the Wallin instrument. (A difference of 2.5 kg. or $5\frac{1}{2}$ lbs.) The greater the amount of force exerted, the greater will be the disparity between the registrations of both dynamometers.

The folly, therefore, of comparing tables of uncorrected dynamometer readings is, no doubt, evident. The same holds true, of course, when individuals, low and high, of a homogeneous group are compared.

Tabulating the accuracy differences of both dynamometers we obtain Table VIII.:

TABLE VIII

ACCURACY DIFFERENCES OF THE TWO DYNAMOMETERS

	Error Index	Correction Constant	Curve	Force		
				10 Kg.	30 Kg.	60 Kg.
Stanford instrument.....	0.916	1.09	$y = \frac{1}{1.09}x$	9.16	27.48	54.96
Wallin instrument.....	0.962	1.04	$y = \frac{1}{1.04}x$	9.62	28.86	57.72

Conclusions

1. Unless corrected, the dynamometer readings do not accurately register the force applied.

2. The error ratio is a constant and may easily be determined.

3. The amount of error increases by arithmetic progression as the force exerted increases.

4. Error ratios (error indices) of dynamometers vary. Therefore the error index of each, and the correction constant for each should be determined.

5. The manufacturers of dynamometers should either furnish accurately calibrated instruments, or mark each machine with its index of error and its correction constant.

6. For purposes of accuracy, dynamometers should be checked for correction at least once every three months. Quoting Auerbach: "Natürlich müssen die Dynomometer vor dem Gebrauch durch bekannte Kräfte geaicht werden, und diese Eichung ist öfters zu wiederholen, da die elastischen Kräfte bekanntlich nicht unbeträchtlichen zeitlichen Änderungen unterliegen" (p. 140). ("Of course dynamometers should be checked with known forces before being used, and this check should be oft repeated, for, as is known, elasticity is significantly affected by temporal changes.")

7. Tabulations of dynamometer reactions should be corrected before publication.

8. It is recommended that some standard procedure for correction be followed by all.

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DISCUSSION

THE TILTING BOARD AND ROTATION TABLE

In the JOURNAL OF EXPERIMENTAL PSYCHOLOGY for October, 1916, Professor Warren and Dr. Reeves describe a combined tilting board and rotation table. It may be of some interest to know that the writer has used successfully an even simpler device for supporting the tilting board and rotation table combined.

The board as described by the authors is to be provided with six ring bolts, one in each corner and one in the middle of each of the long sides. Four pieces of rope, about six feet long (the length depending upon the height of the ceiling), have spliced into one end of each a snap hook, obtainable at any harness makers (preferable to an open hook, as it avoids accidents); the other ends of the rope are spliced into a large ring, this ring is suspended from a stout hook placed in the ceiling, by means of a rope of sufficient length to bring the board at the desired height. When used as a tilting board, two of the ropes are hooked into the rings at the side, the other two being tied up out of the way; used as a rotating table, the four ropes are hooked into the four corners of the board. It is convenient to have the rope that suspends from the ceiling hook supplied with an extra ring, somewhere near the middle, so placed that when the apparatus is hung up, the board, when in a vertical position, just clears the floor. If new rope is used it should clear perhaps by three inches to provide for stretching later. The full length of this ceiling rope may then be so adjusted that when the board is used as a rotation table it may be within a foot or two of the floor which renders it easy for the subject to reach and removes the fear, that some subjects sometimes have, of trying the experiment if the board is up high.

Suspended by the two ropes at the centers of the sides of the board, the apparatus is as delicate as though it had knife-

edge bearings and it may thus be used for the experiment proving that mental activity induces the flow of blood to the brain. For this experiment, supports a little shorter than the height of the board are placed under each end (small tables answer well) so that the board can have a movement from the horizontal of only a few inches. Spring balances of suitable sensitivity are fastened to each end of the board and also to the table; these will control the oscillation of the board due to the breathing. The tilting of the board may be magnified and made visible to a class, by the use of a light indicator in the form of a lever with the fulcrum rather close to the end near the board and adjusted to touch the board on the under side, so that as the end goes down, even very slightly, the other end goes up rapidly.

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